The Current and Future Neutrino Program at Fermilab

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The Present Neutrino Landscape

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Delta m_{21}^2 = 7.54\ ^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m_{32}^2| = 2.42\ ^{+0.07}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$

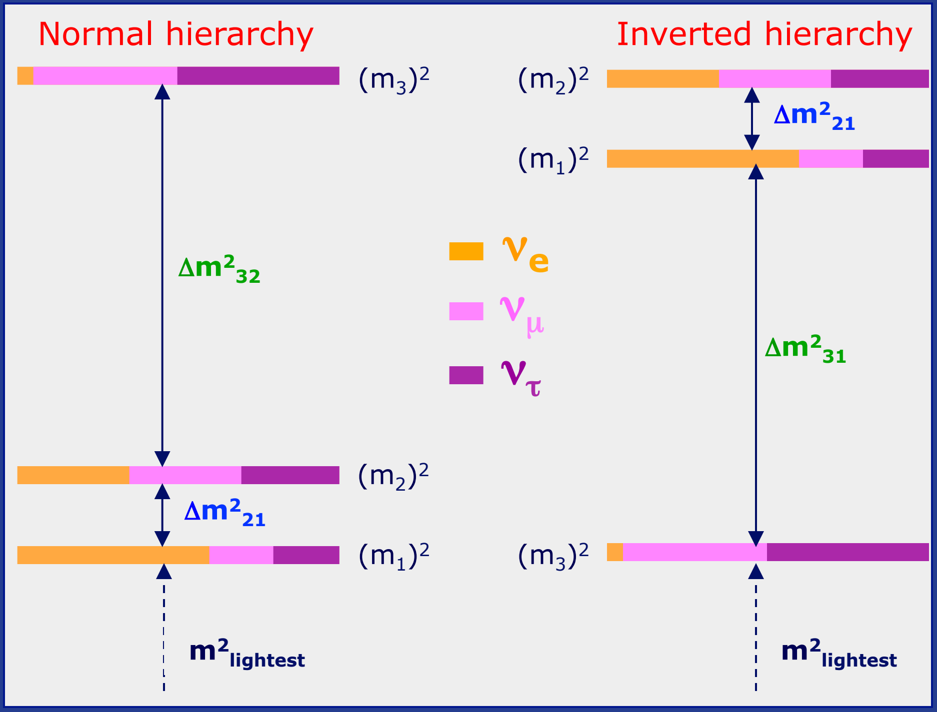
$m(\nu_e) < 2.3$ eV (95% CL)

$\theta_{12} = 33.6\ ^{+1.1}_{-1.0}$ deg

$\theta_{23} = 38.6\ ^{+2.4}_{-1.4}$ deg

$\theta_{13} = 9.0\ ^{+0.4}_{-0.5}$ deg

$m_{lightest} = ?$
sign $\Delta m_{32}^2 = ?$
$\delta = ?$



Marginalized 1D !σ uncertainties, Fogli et al 1205.5254, C.Kraus et al Eur. Phys. J. C40, 447 (2005)

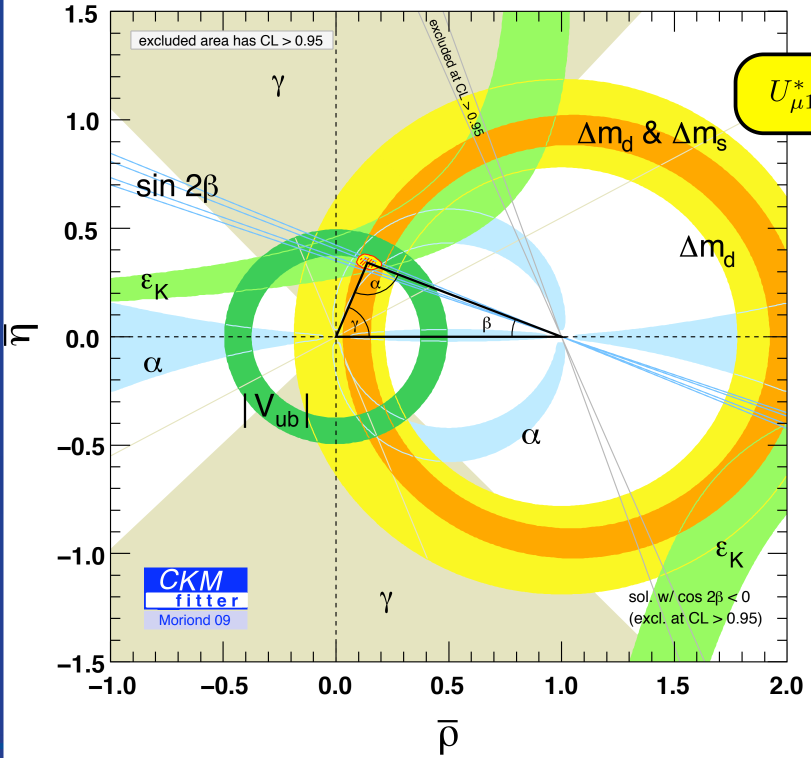
Worldwide Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
    - What are the neutrino masses?
    - Are neutrinos their own anti-particles?
    - Is θ_{23} maximal?
    - How are the masses ordered?
    - Is CP violated?

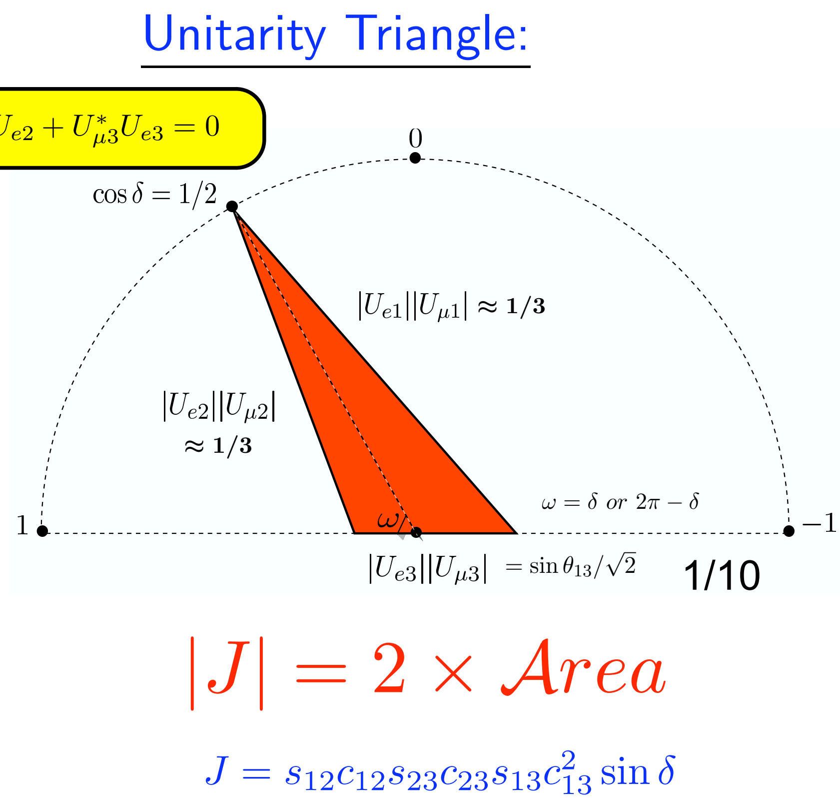
2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
    - Can we independently check the θ_{13} measured by reactor experiments?
    - Are the LSND and MiniBooNE anomalies new physics?
    - Are neutrinos and anti-neutrinos oscillating differently in current experiments?
    - Do neutrinos interact with matter in any non-standard ways?

3) Carry out the neutrino engineering measurements that make 1) and 2) possible

Why Answer the Big Neutrino Questions?



Quarks



S. Parke

Neutrinos

Why Answer the Big Neutrino Questions?

Models predict relationships between neutrino parameters

- ☐ Quark-Lepton Complementarity $\theta_{12} + \theta_C = 45^o$
- ☐ Solar sum rules
  - Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta$
  - Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta$
  - Golden Ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

Plus HO corrections…

- ☐ Atm. sum rules
  - Tri-bimaximal-Cabibbo $\theta_{12} = 35^o \quad \theta_{23} = 45^o$, $\theta_{13} = \theta_C/\sqrt{2} = 9.2^o$
  - Trimaximal1 $\theta_{23} = 45^o + \sqrt{2}\theta_{13} \cos\delta$
  - Trimaximal2 $\theta_{23} = 45^o - \frac{\theta_{13}}{\sqrt{2}} \cos\delta$

Plus Charged Lepton Corrections…

Now that θ_{13} is measured these predict $\cos\delta$

Precision Parameter Measurement

↓

Model Discrimination

↓

Underlying Physics

Why Answer the Big Neutrino Questions?

- A(The?) Big Question:-
  - Today: B = #(Baryons) - #(Antibaryons) ≠ 0
  - Standard cosmology: Right after the big bang B = 0
  - How did B=0 ➔ B≠0 ?
- B=0 ➔ B≠0 requires CP violation (A.D.Sakharov JETP 5: 24-27 (1967))
- The CP violation in the CKM matrix leads to a Baryon Number B far smaller than that observed
- Leptogenesis ***can*** explain the observed Baryon Number through CP violating heavy neutrino decays (M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986))
- ***Generically***, leptogenesis and light neutrino CP violation imply each other
- So look for light neutrino CP violation

Current and Planned Fermilab Neutrino Experiments

Experiment	Beamline	Status	# institutions (# countries)	# publications
ArgoNeut	NuMI	Completed 2010	9(3)	1 phys, 2 instr
MINOS	NuMI	Completed 2012	30(5)	28 phys, 23 instr
MINERvA	NuMI	Running	21(8)	1 phys, 1 instr
NOvA	NuMI	Under Construction	32(5)	-
MINOS+	NuMI	Fermilab Approved	34(6)	-
MiniBooNE	BNB	Completed 2012	19(2)	22 phys, 1 instr
SciBooNE	BNB	Completed 2008	17(5)	7 phys
MicroBooNE	BNB	Under Construction	16(3)	-
LBNE	LBNE Beamline	CD1	62(5)	-

The Fermilab Neutrino Program involves 120 institutions from 15 countries

NuMI = Neutrinos from the Main Injector: 120 GeV protons on a carbon target

BNB = Booster Neutrino Beamline: 8 GeV protons on a beryllium target

LBNE Beamline: 60 -120 GeV protons from the Main Injector

Project X Example Power Staging Plan

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.

** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.

Fermilab Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
   - What are the neutrino masses? **No plans to address at Fermilab**
   - Are neutrinos their own anti-particles? **No plans to address at Fermilab**
   - Is θ_{23} maximal? **MINOS → NOvA → LBNE**
   - How are the masses ordered? **NOvA → LBNE**
   - Is CP violated? **LBNE**

2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
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   - **MiniBooNE, SciBooNE, MINERvA, ArgoNeut, MicroBooNE**

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Reveal the Pattern of Neutrino Masses and Mixings

- What are the neutrino masses?
  - Tritium β decay and $0\nu\beta\beta$ decay experiments
  - Not an area in which Fermilab participates
  - Cosmological constraints (here Fermilab does contribute)
- Are neutrinos their own anti-particles?
  - Several $0\nu\beta\beta$ decay experiments worldwide
  - Not an area in which Fermilab participates

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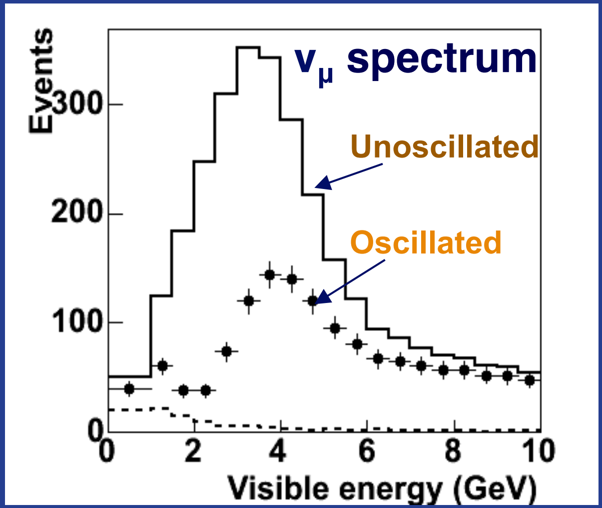
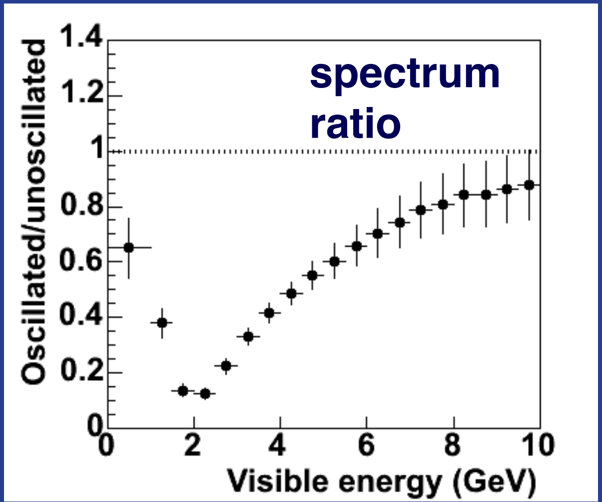
Is θ_{23} Maximal?

- Study using ν_μ disappearance

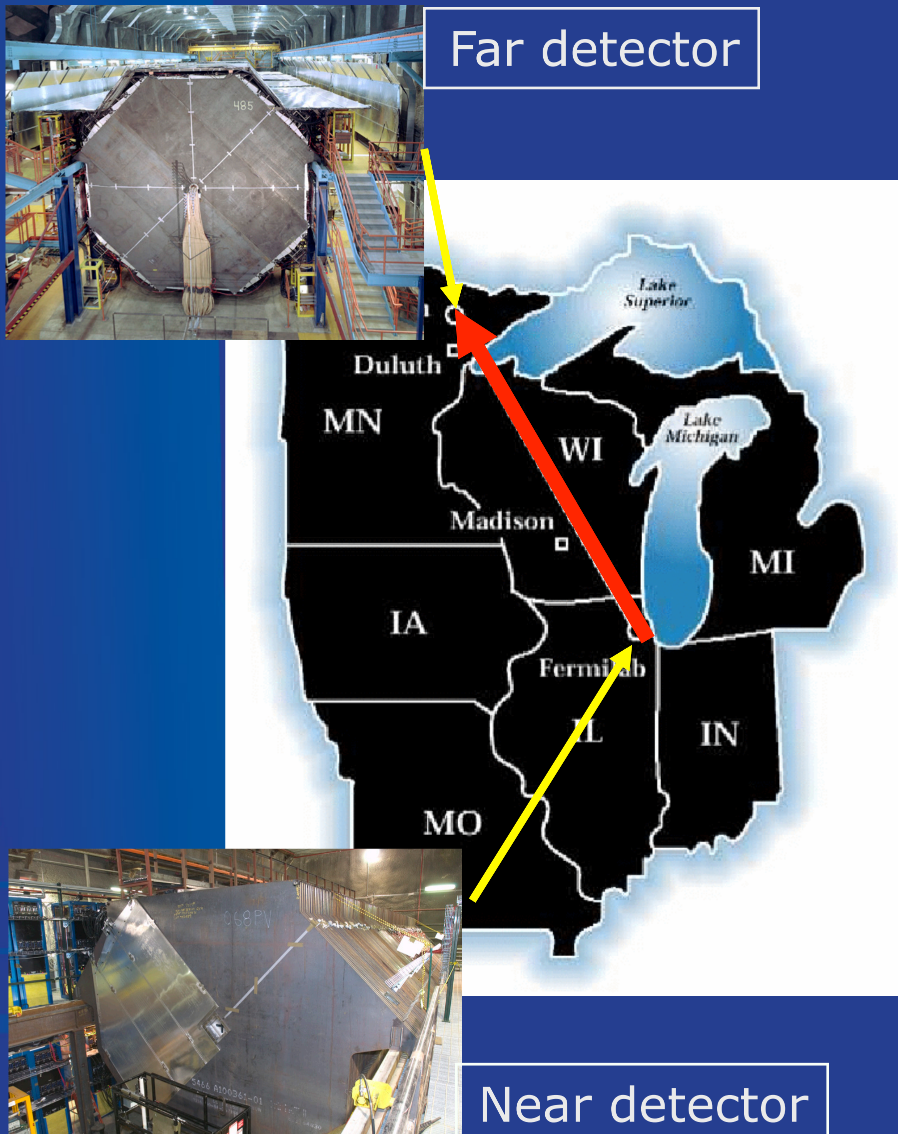
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$$





- If it is maximal something is making it that way
  - A clue to the mixing parameters more generally?

The MINOS Experiment



Far Detector:

Soudan, Minnesota, 735 km from target

5.4 kton mass

484 steel/scintillator planes, 8x8x30 m^3

107 collaborators from 30 institutions in 5 countries

Near Detector:

Fermilab, 1km from target

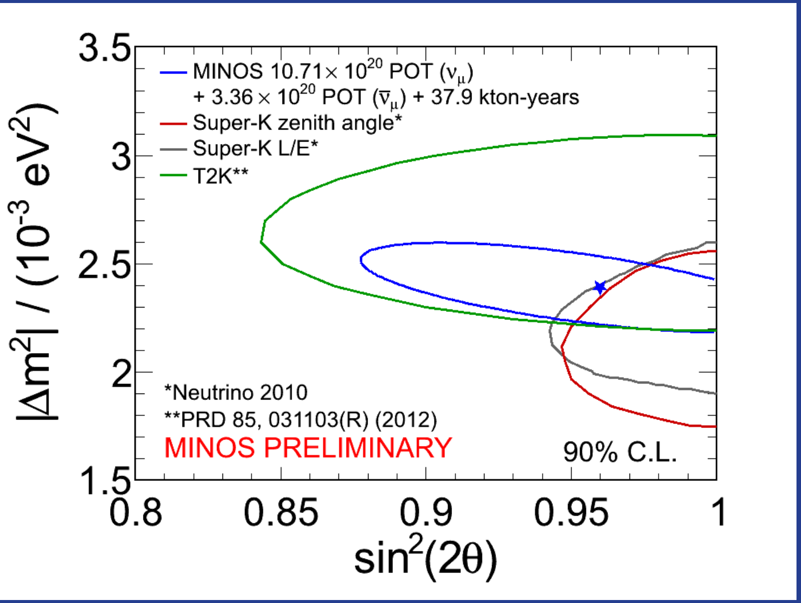
1 kton mass

282 steel planes

153 scintillator planes, 3.8x4.8x15 m^3

Is θ_{23} Maximal?

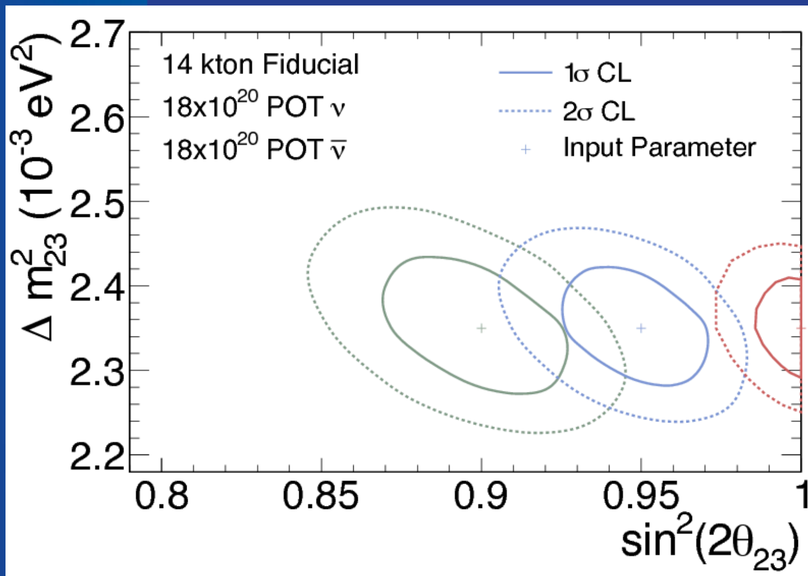
- MINOS latest results announced at Neutrino 2012



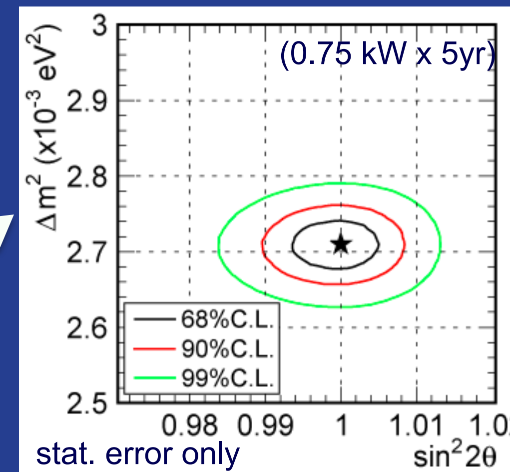
- Full dataset
  - Both horn current modes + atmospheric neutrinos
- Two flavor oscillation assumption
  - Full three flavor analysis being worked on

Is θ_{23} Maximal? – NOvA and T2K Sensitivities

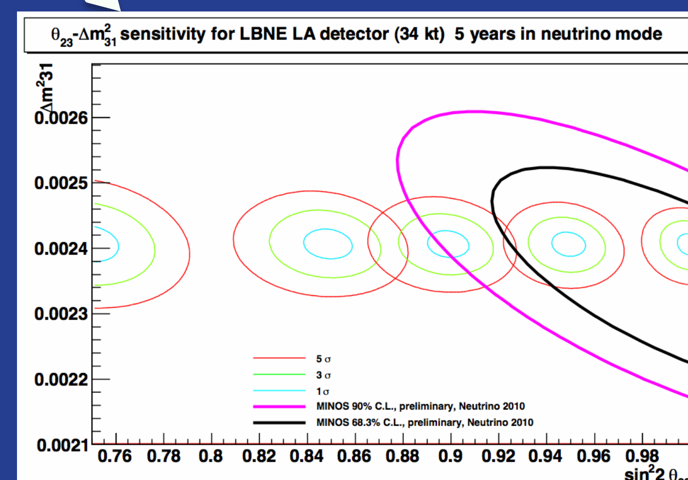
NOvA



T2K



LBNE



- NOvA and T2K measurements may well provide a "no" answer to the question
  - "Octant question" attacked by combining NOvA/T2K and reactor experiments
- If the question is still relevant at the end of the decade then LBNE can weigh in

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How are the Masses Ordered?

The mass hierarchy (sign of Δm_{32}^2) can be extracted from a comparison of P(ν_μ to ν_e) to P(anti-ν_μ to anti-ν_e)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \\
& + \cos\delta \sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right) \\
& + \sin\delta \sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)
\end{aligned}
$$

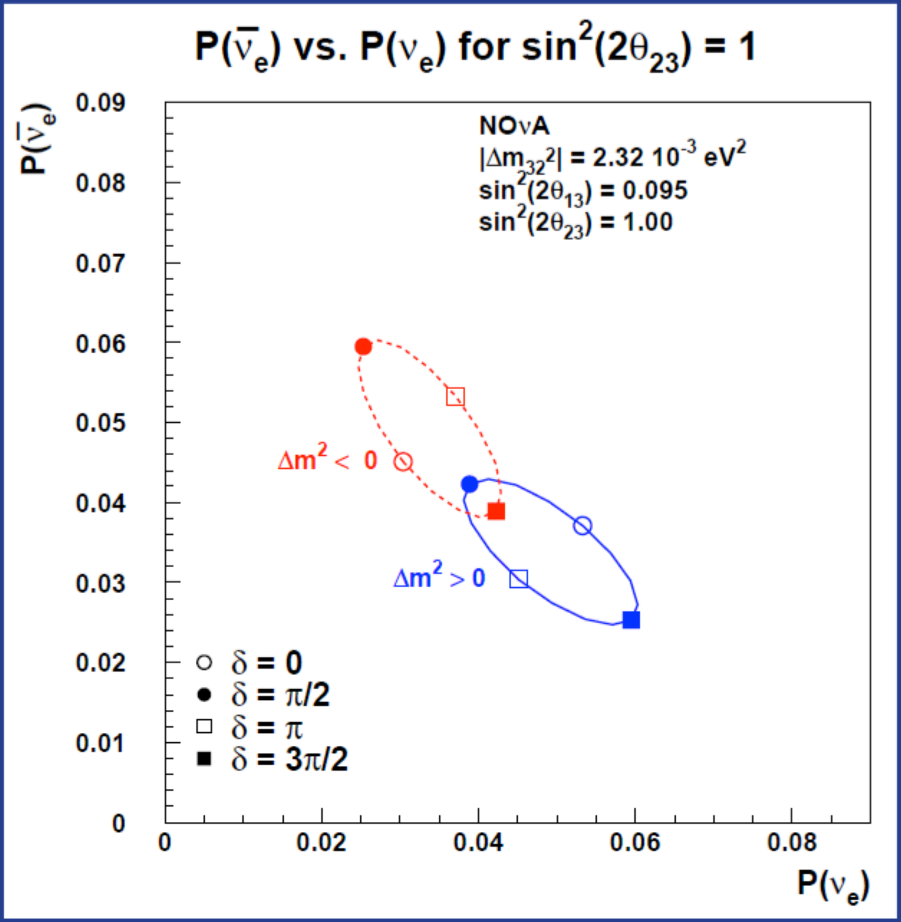
$P(\bar{\nu}_\mu \to \bar{\nu}_e): \quad \sin\delta \to -\sin\delta, \quad a \to -a$

$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$

Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\ \mathrm{km})^{-1}$

L(km), E(GeV), m(eV)

How are the Masses Ordered?



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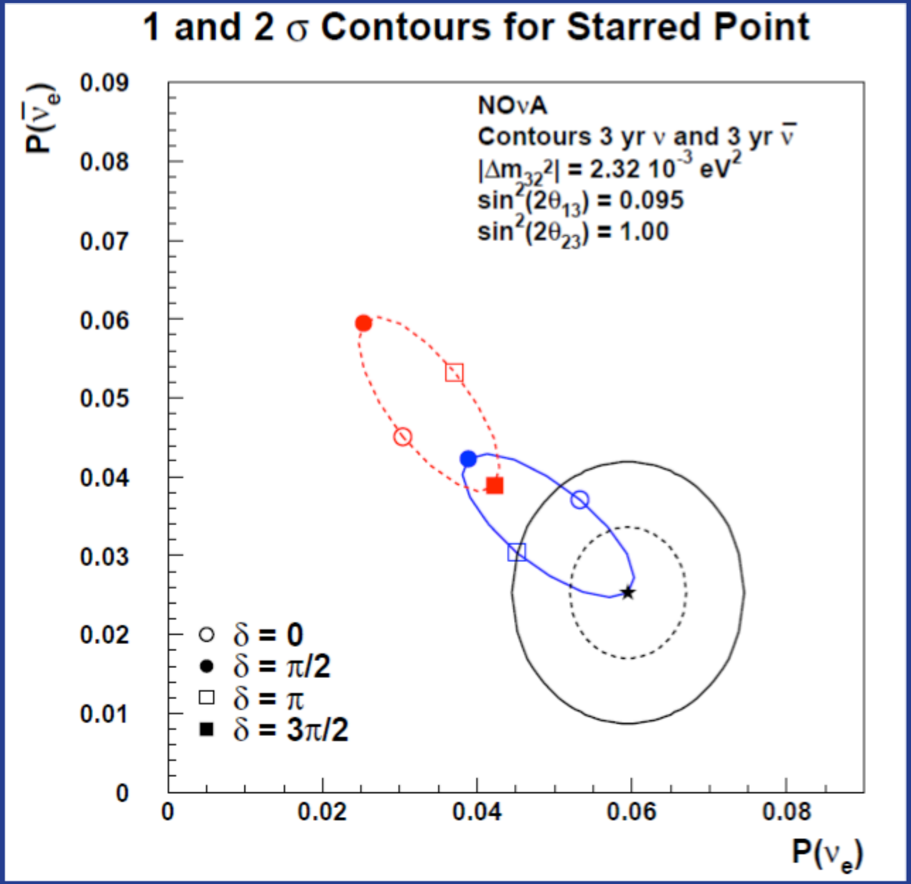
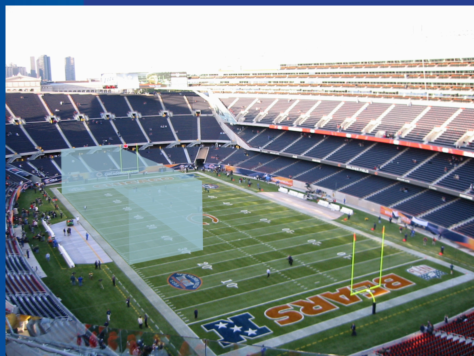


Fermilab

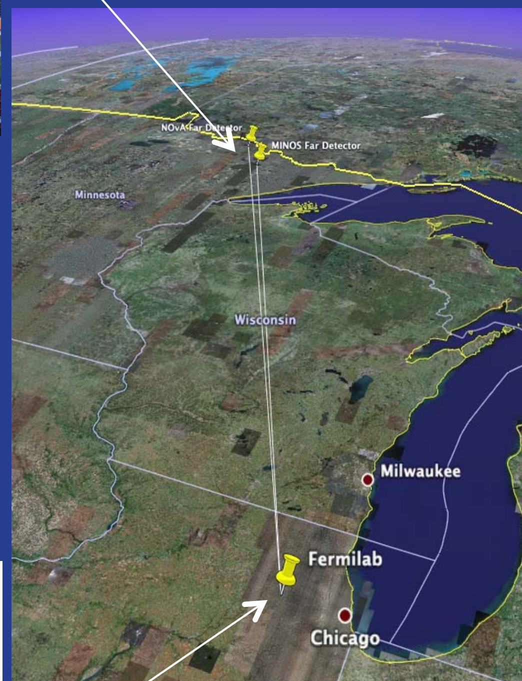
The NOvA Experiment



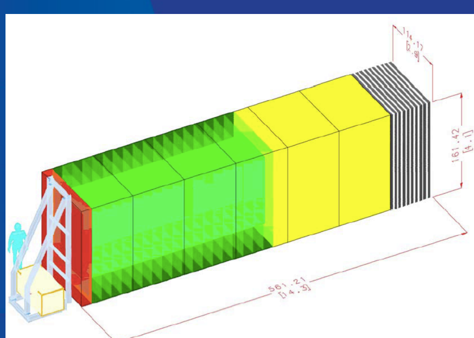
Far Detector:

14 kTon liquid scintillator

Fine grained calorimeter



166 collaborators from 32 institutions in 5 countries

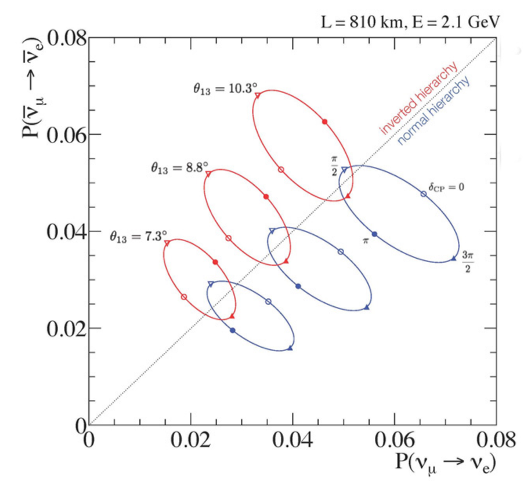


Near Detector:

330 ton version of the far detector

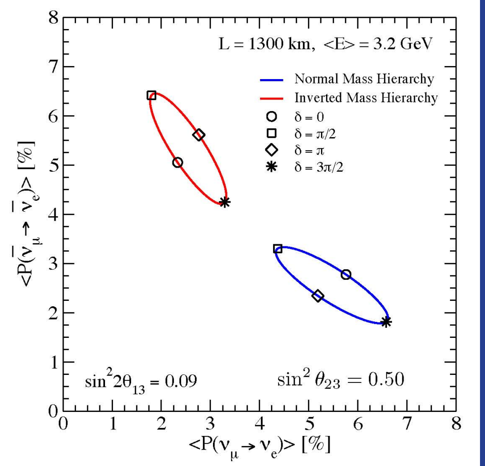
Now That We Know θ_{13} Is 9°…

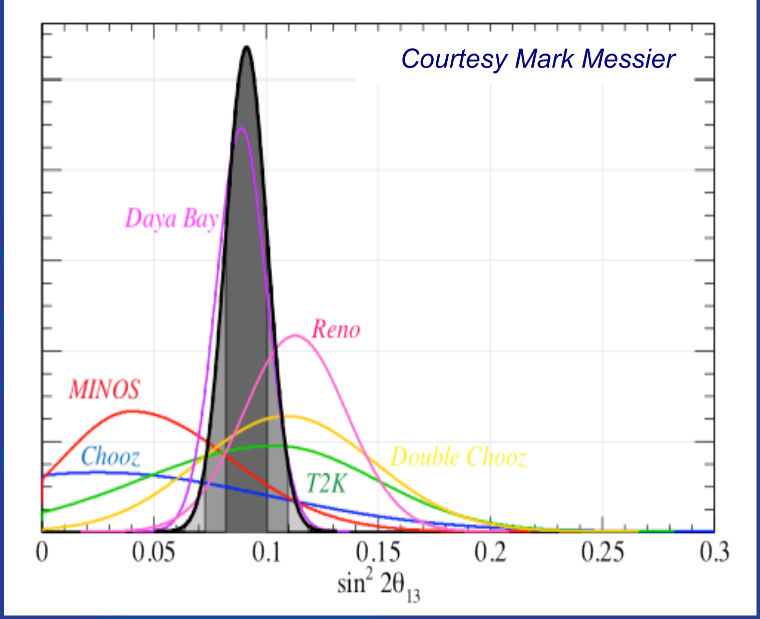
Now that we know that θ_{13} has a large value long baseline neutrino physics is richer and near term experiments have some sensitivity to hierarchy



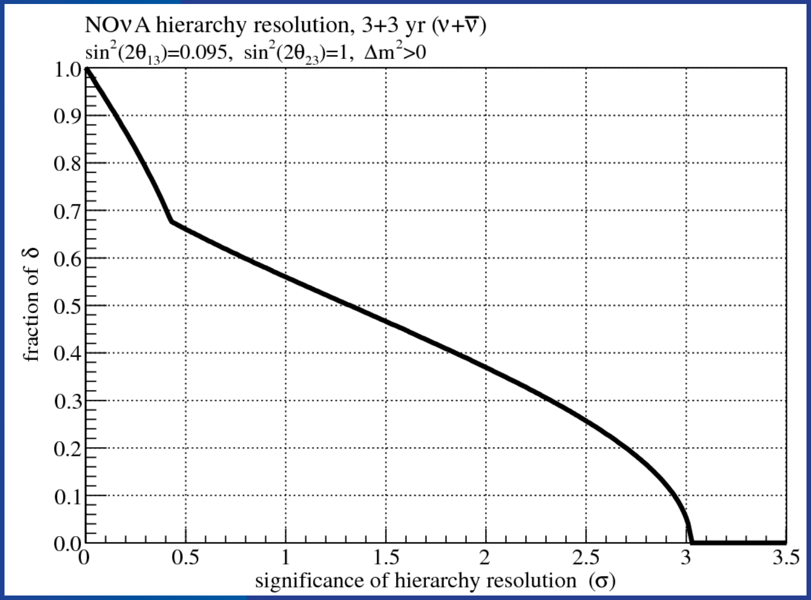
Neutrino oscillations in NOVA

same L/E as NOvA

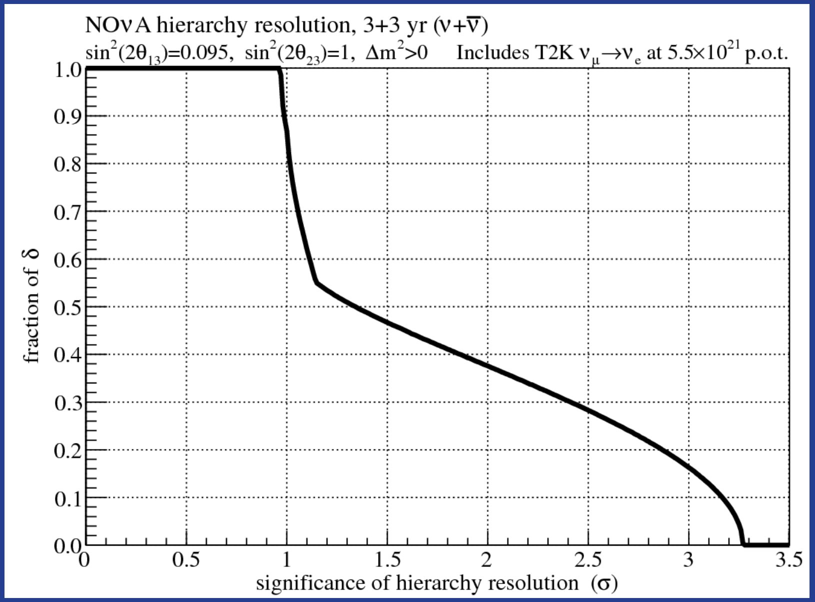




How are the Masses Ordered? NOvA + T2K Sensitivity



NOvA alone



NOvA + T2K

Fermilab

The LBNE Experiment

Phase 1: 10 kton Liquid Argon TPC Far Detector just below the surface

New 700kW broadband neutrino beam from Fermilab

347 collaborators from 62 institutions in 5 countries

LBNE Reconfiguration

July 2011: Decision to use "MI-10 Shallow" beamline option moving target , decay pipe and absorber above aquifer

Jan 2012: Decision to use LAr TPC technology rather than water Cerenkov

March 2012: Charge from DOE Office of Science to reconfigure

April 2012: Reconfiguration Committee and working groups formed

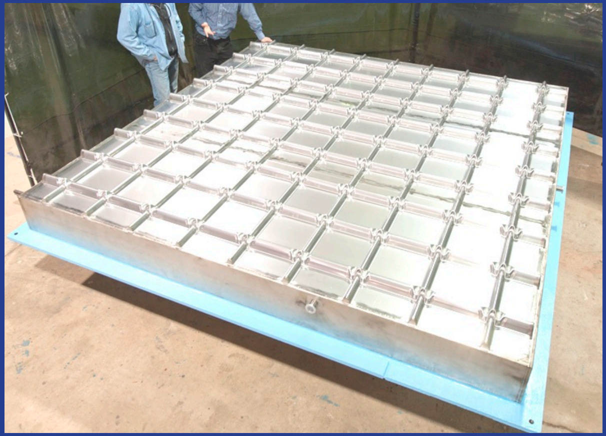
August 2012: Reconfiguration Committee's final report delivered

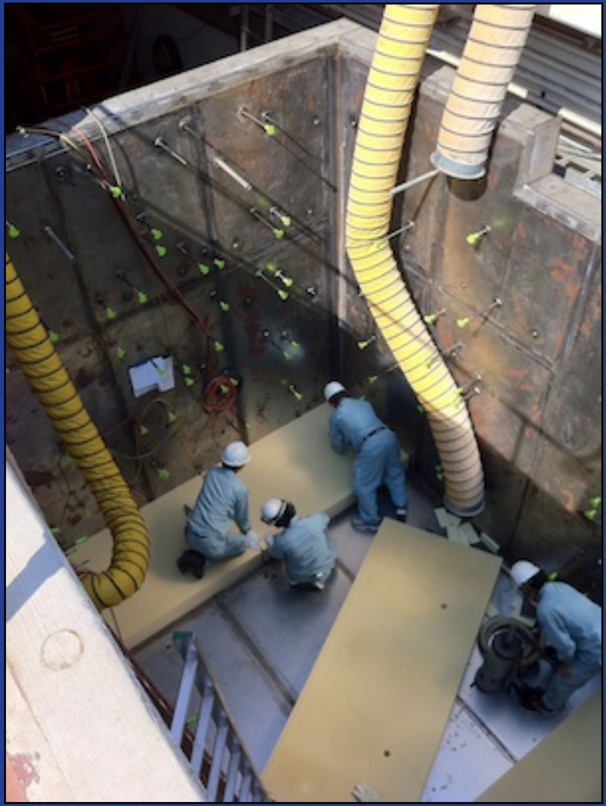
http://www.fnal.gov/directorate/lbne_reconfiguration

- Preferred option is a first phase with a 10kton LAr detector on the surface at Homestake with a new 700 kW beam from Fermilab
- Enhancements (larger detector, move underground, near detector, etc) available as future phases or with outside funds
- Phased LBNE can be interleaved with a phased Project X

LBNE Project Supported LAr R&D

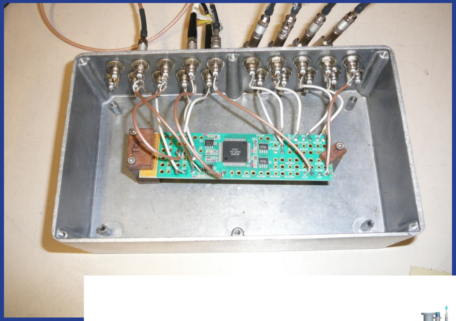
- LAr Far Detector prototyping in LBNE Project is part of larger program.
- Project built 3mx3m membrane wall panel in 2011 to demonstrate technology.
- Currently constructing 35 ton membrane cryostat prototype.
  - Expect to be operational in 2013.
- Planning how to use it beyond cryo testing
  - Subsystem components
  - System test of scaled-down detector

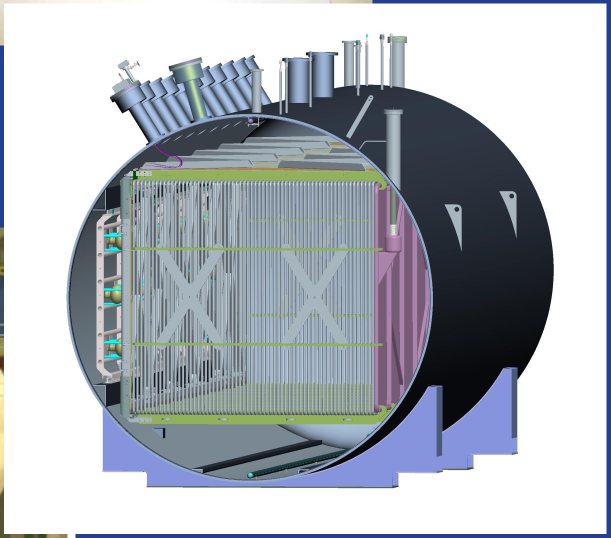




LAr R&D Program Successes So Far

- Purity without evacuation
- Foam insulation
- Membrane cryostats
- Cold electronics
- Long drift





Early career award to Sam Zeller

Liquid Argon In A Testbeam (LArIAT)

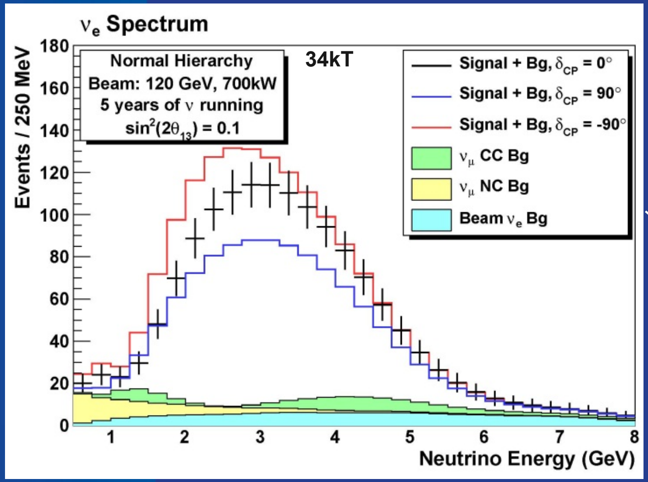
- 2009 LAr R&D review asked *How well known are the energy resolution and particle identification capabilities of a LArTPC?*

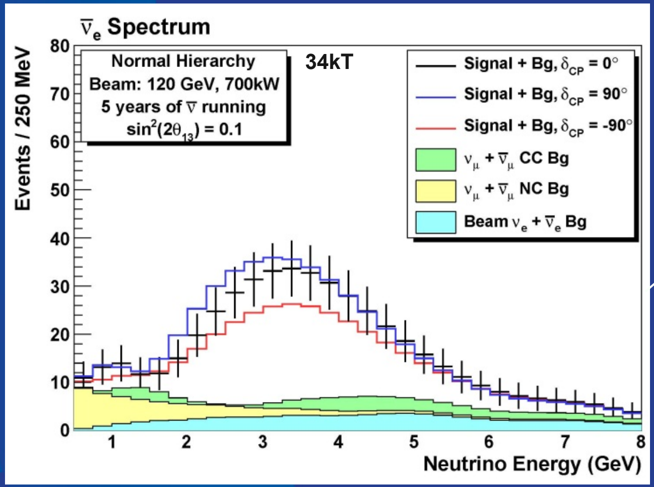
- No comprehensive test beam runs ever performed to look at particles and energies expected in neutrino experiments: e, p, π, μ, look at K with an eye toward nucleon decay

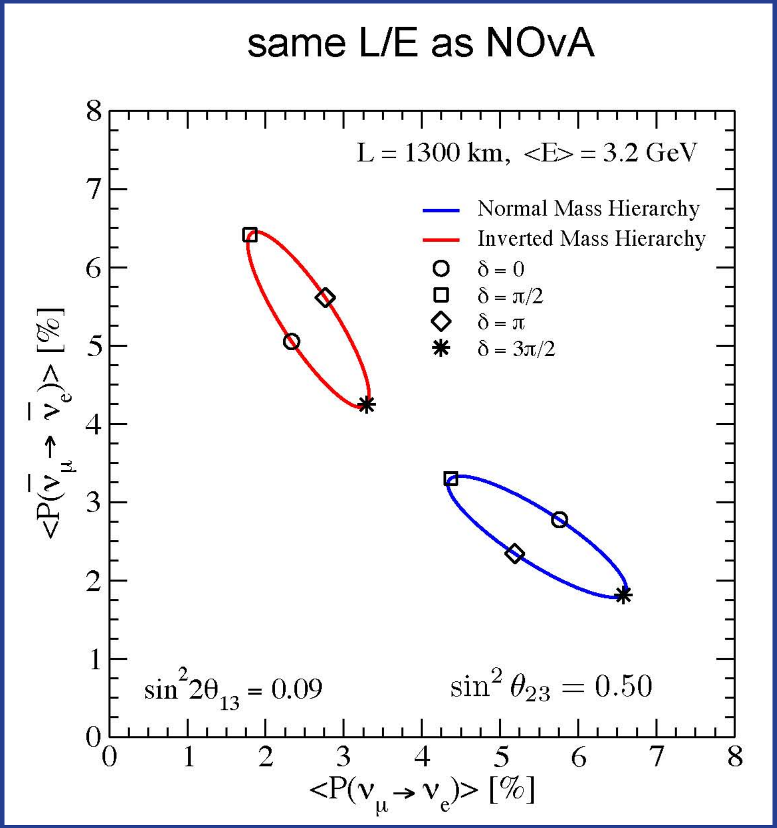
- Use a two-phased approach
  - First phase uses ArgoNeuT to understand charge to energy conversion and single track topologies
  - Second phase will be a much larger TPC to contain EM and hadronic showers

- Both phases look at e/γ separation

LBNE Bi-Probability Plot



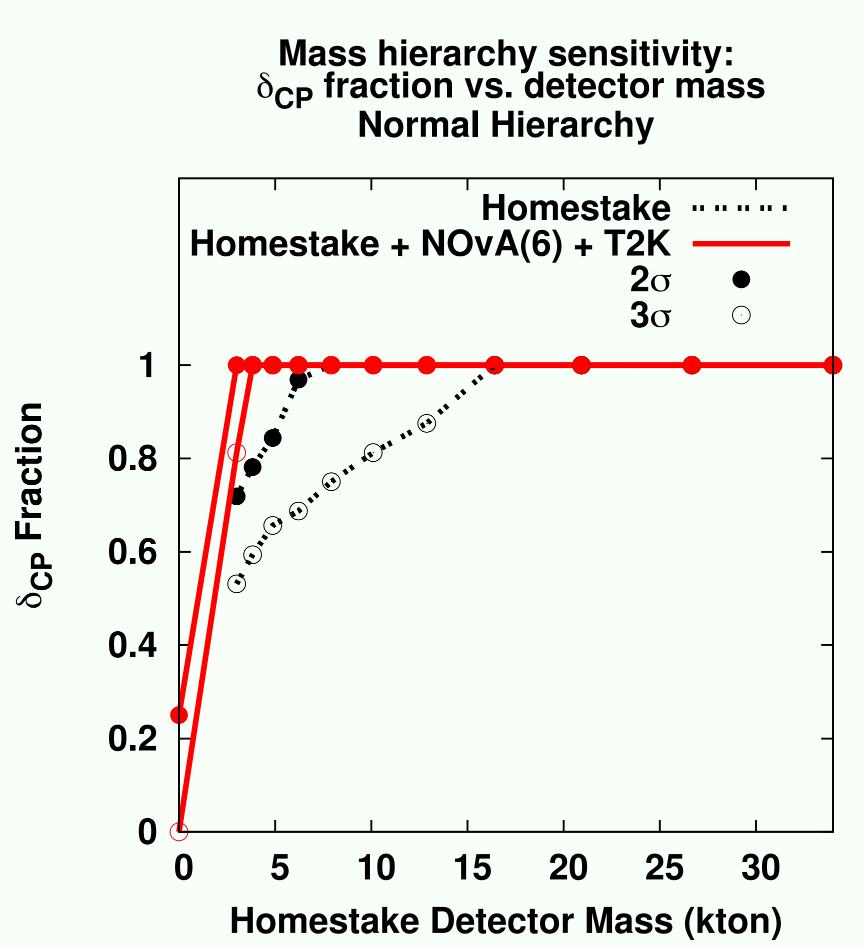




LBNE vs NOvA: Longer baseline ➔ more matter effect➔ hierarchy ellipses better separated

How are the Masses Ordered? – LBNE Sensitivity

LBNE will nail the hierarchy if it hasn't already been determined by NOvA and T2K



The fraction of δ_{CP} values for which the mass hierarchy can be resolved at $2/3\sigma$ (solid/open points) after 10 year run

In principle one could use reactor neutrino disappearance at a ~60km baseline to distinguish hierarchy. This would be an extremely (prohibitively?) difficult measurement (arXiv:1208.1551)

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3) Carry out the neutrino engineering measurements that make 1) and 2) possible
   - **MiniBooNE, SciBooNE, MINERvA, ArgoNeut, MicroBooNE**

Measuring CP Violation in ν_e Appearance

δ_{cp} (and hierarchy together) can be extracted from a comparison of P(ν_μ to ν_e) to P(anti-ν_μ to anti-ν_e)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \\
& + \cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right) \\
& + \sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)
\end{aligned}
$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e): \quad \sin\delta \to -\sin\delta, \quad a \to -a$

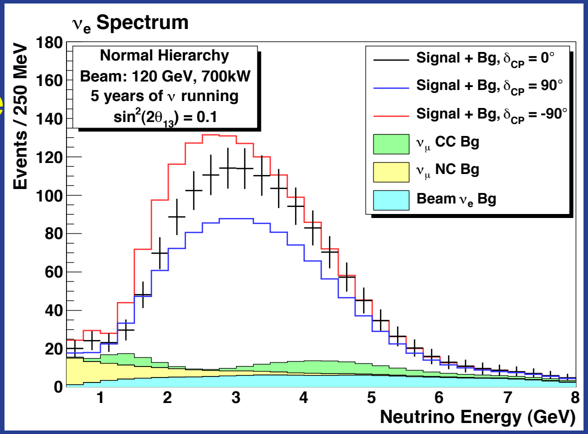
$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$

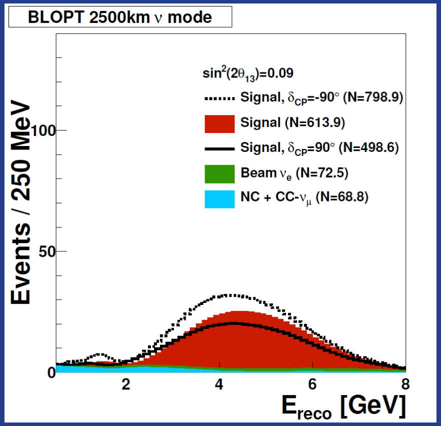
Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\ \mathrm{km})^{-1}$

L(km), E(GeV), m(eV)

CP Violation and Measuring δ_{cp}

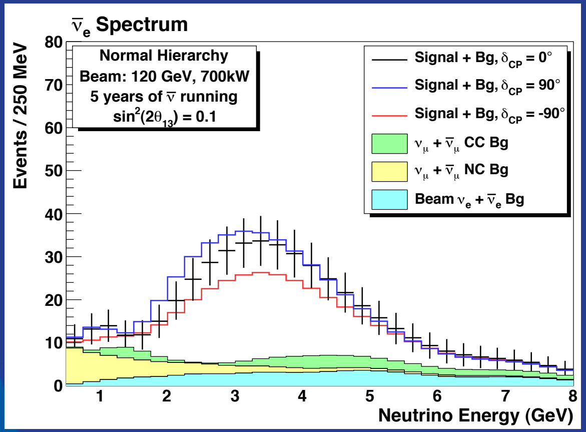
LBNE
ν mode

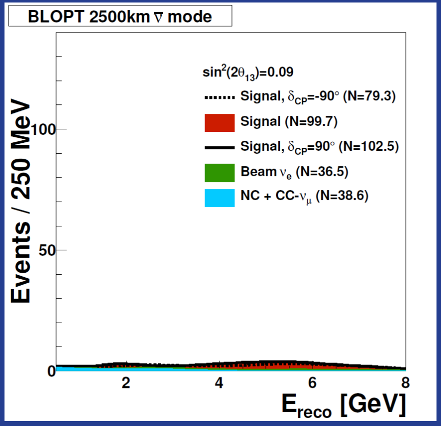




LAr@2500km
ν mode

LBNE
anti-ν
mode

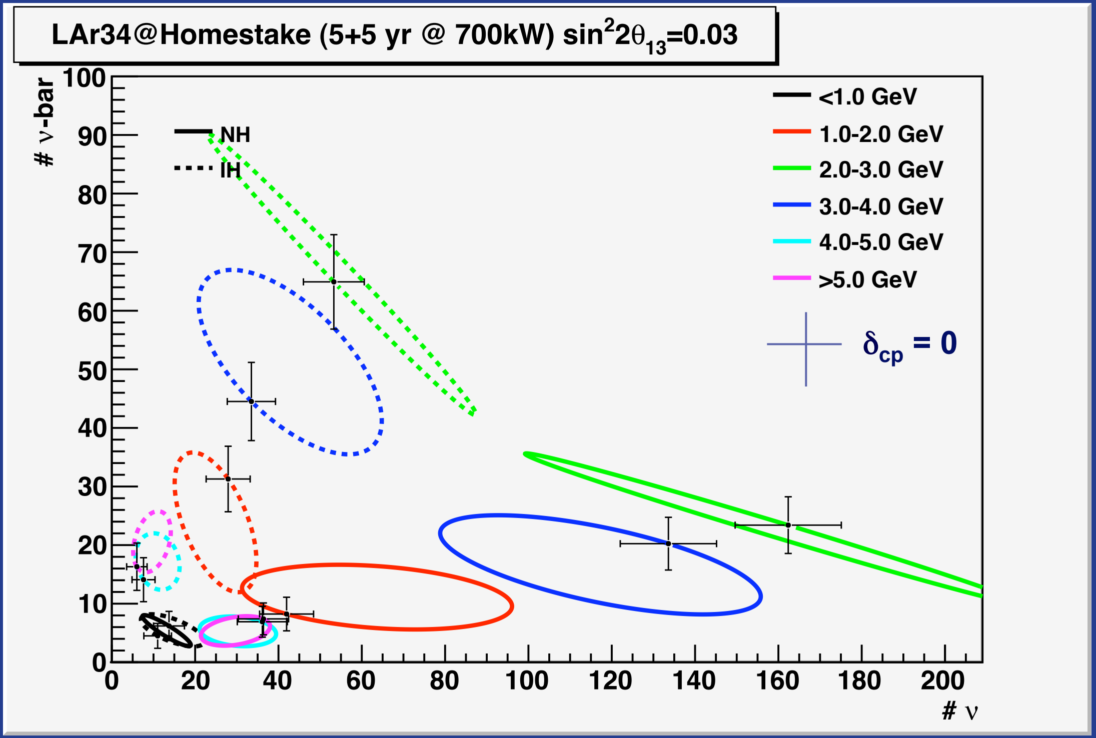




LAr@2500km
ν mode

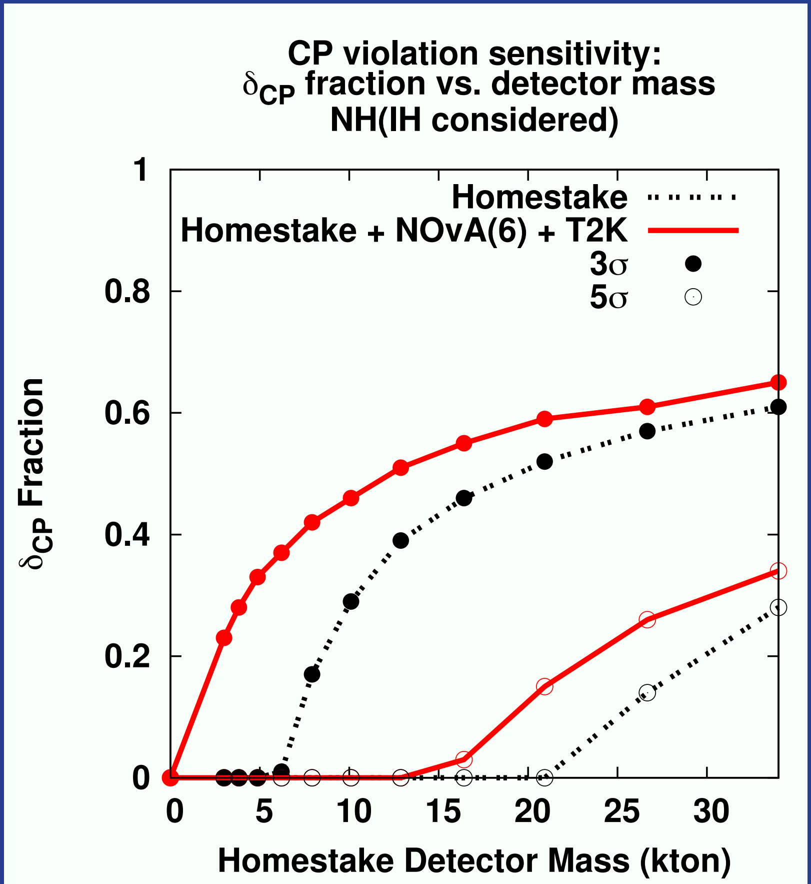
- CP Violation is demonstrated by seeing ν_e and anti-ν_e appearance behave differently
- In principle δ_{cp} can be measured with just ν_e appearance without running in anti-neutrino mode

LBNE Bi-Rate Plot with Statistical Errors



Fermilab

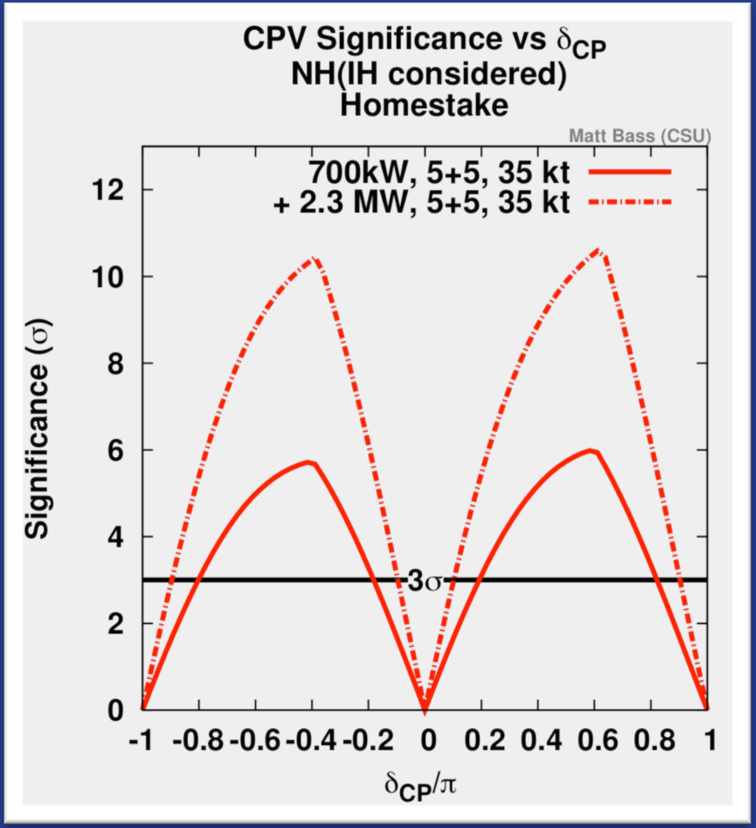
Is CP Violated? – LBNE Sensitivity



The fraction of δ_{CP} values for which CP violation can be resolved at 3/5σ (solid/open points) after 10 year run

Ultimate LBNE Sensitivity

With a full 35 kton detector and Project X. The CP violation discovery potential is impressive



Fermilab Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
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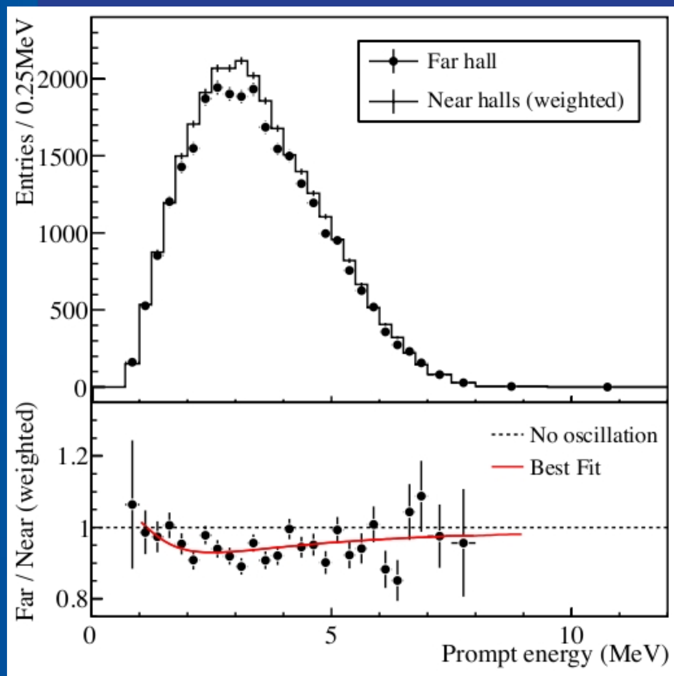
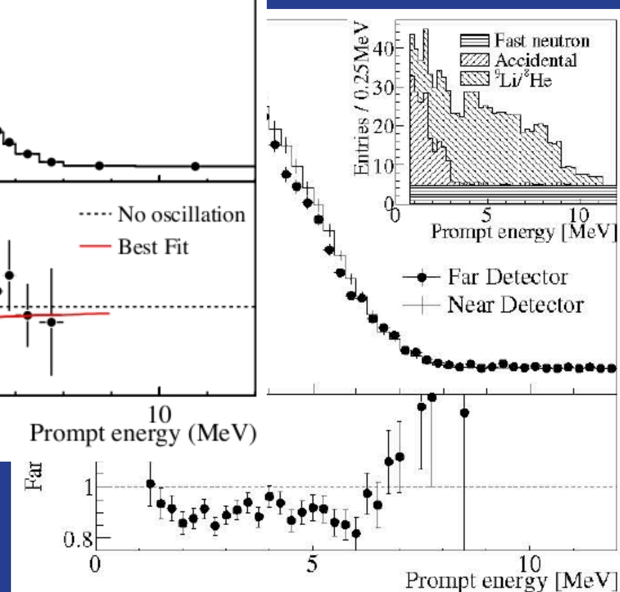
Reactor Measurement of θ_{13}

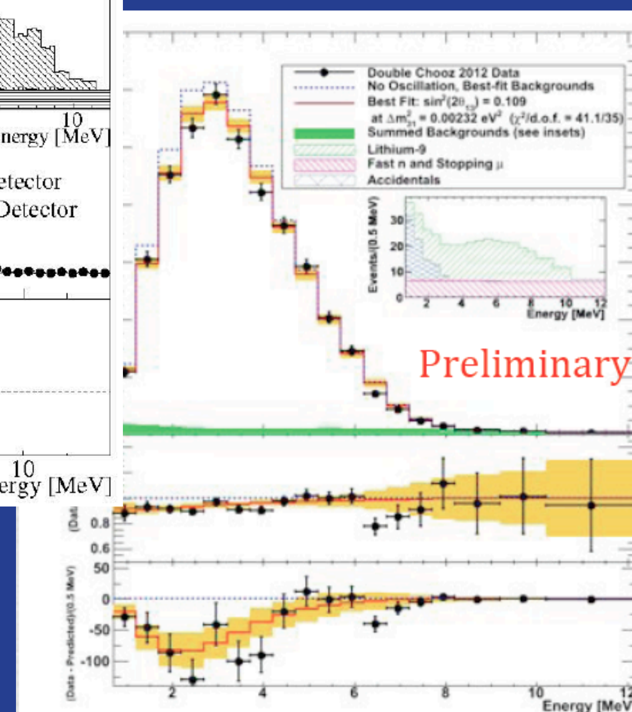
Daya Bay



Reno



Double Chooz



In 4 months this year we went from θ_{13} being almost unknown to it being the best measured mixing angle!

Fermilab

Measuring θ_{13} with ν_e Appearance

θ_{13} controls the size of 3 of the 4 terms in $P(\nu_\mu$ to $\nu_e)$

$$
\begin{aligned}
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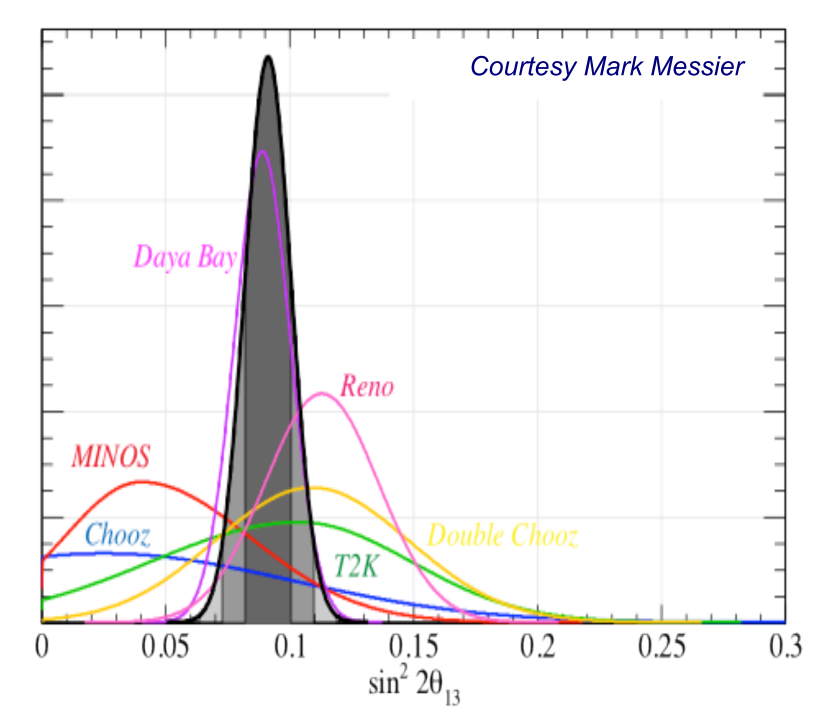
Matter effect $a \equiv G_F N_e/\sqrt{2} \approx (4000\ \text{km})^{-1}$

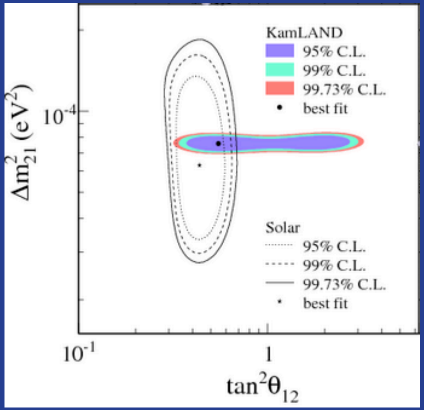
L(km), E(GeV), m(eV)

Can we Independently Check the θ_{13} Measured by Reactor Experiments?



- Will NOvA and T2K measure ν_e appearance at the expected rate?
  - Yes – Then we will have powerful confirmation of our understanding of the 3x3 oscillation matrix
  - No – Then we will have a strong indication of some new physics

There is a close analogy here with the solar neutrino problem and the exquisite concordance of the SNO and KamLAND results



KamLAND, PRL. 100, 221803 (2008)

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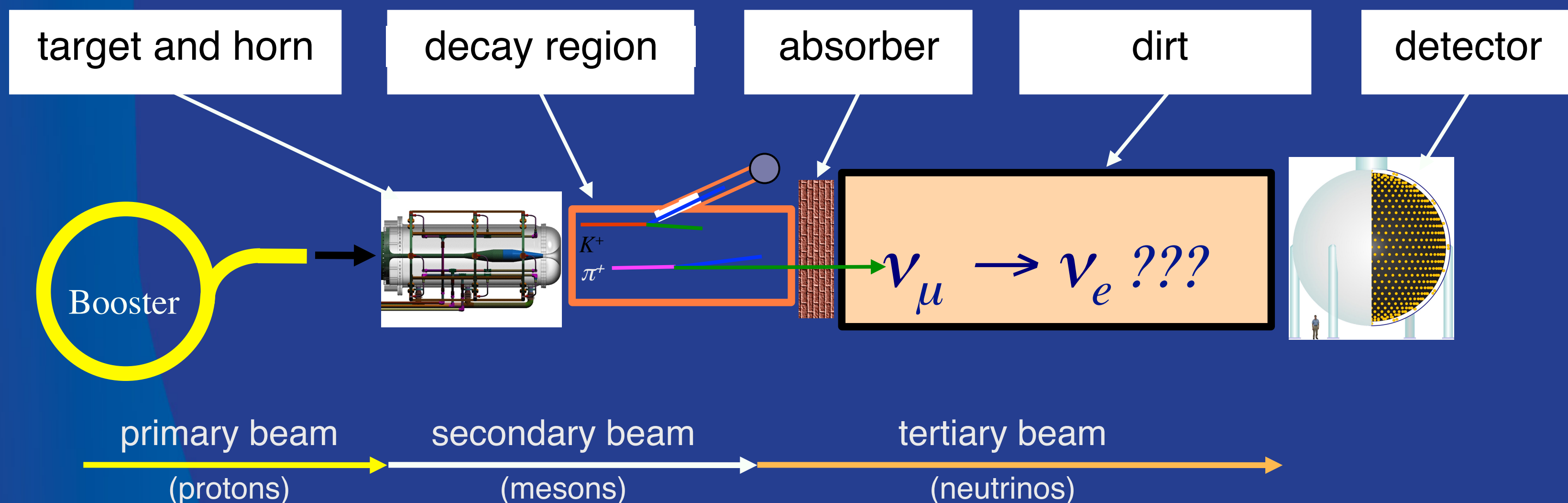
The MiniBooNE Experiment

Keep L/E same as LSND
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

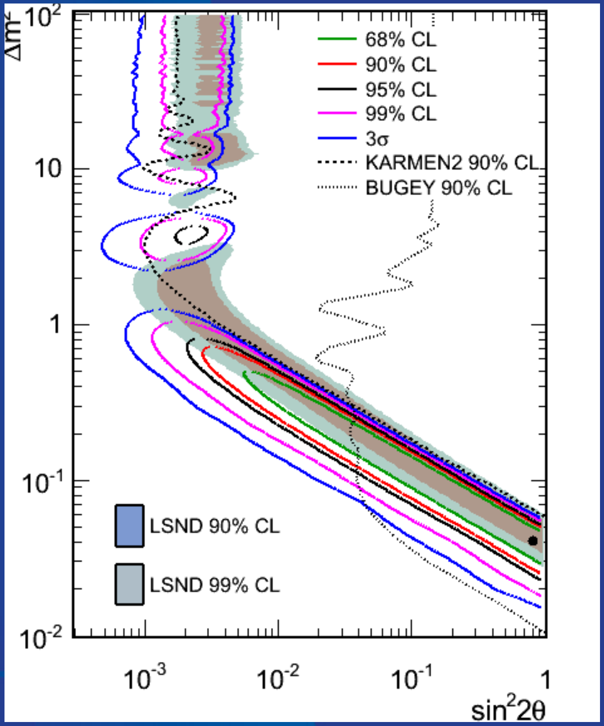


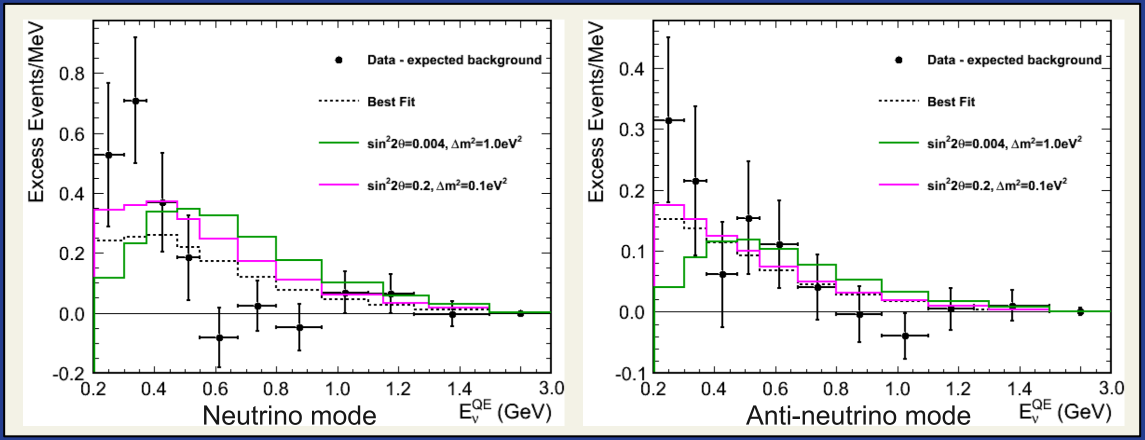
Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

86 collaborators from 19 institutions in 2 countries

MiniBooNE Simultaneous 3+1 fit to ν and anti-ν data





Total Excess: 240.3 +/- 34.5 +/- 52.6

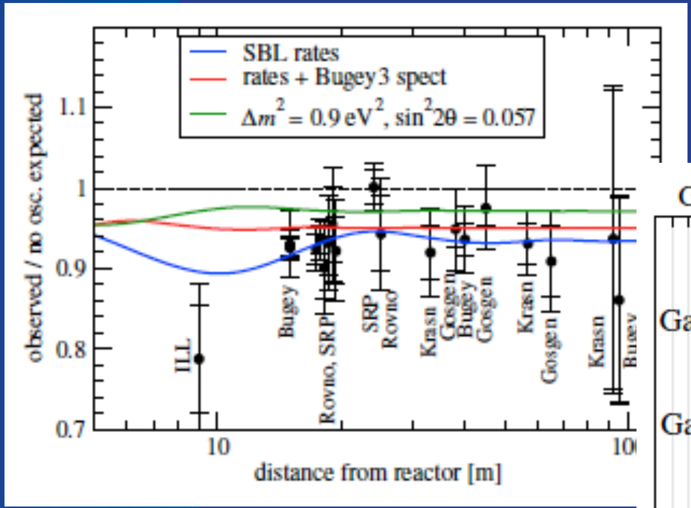
E>200 MeV Best Fit preferred at 3.6σ over null

Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MiniBooNE neutrino and anti-neutrino data

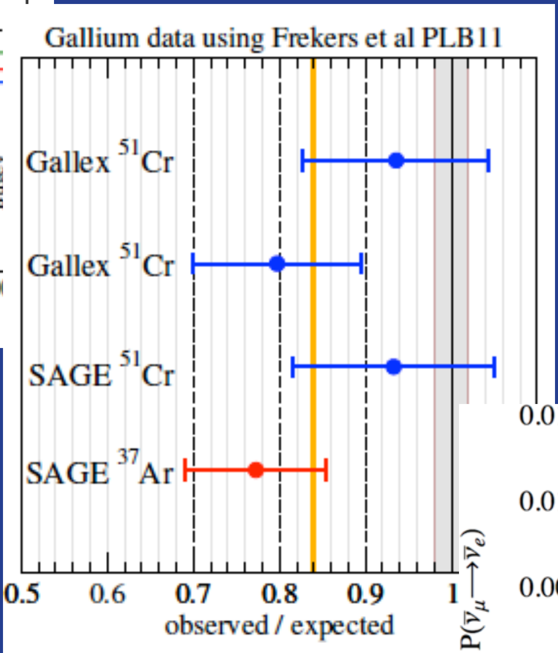
combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

Hints of Something at ~1eV^2?

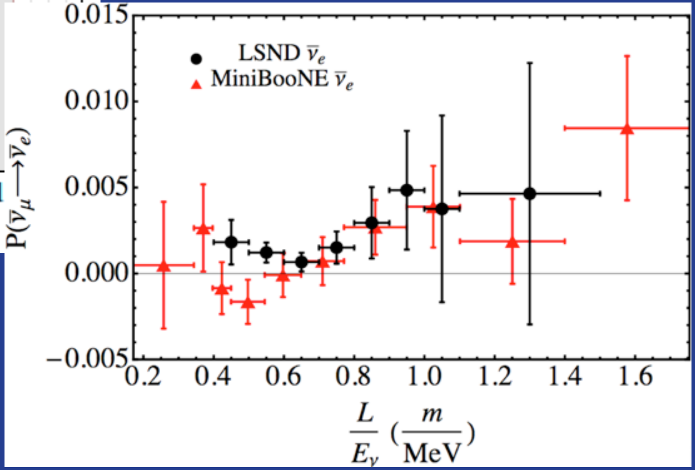
Reactor Neutrino Anomaly



Gallium Anomaly



LSND & MiniBooNE



Additionally, cosmology hints at more than 3 neutrino states

Fermilab Short Baseline Focus Group

- Two Recommendations from last year's S&T review:-
  - It is recommended that Fermilab be more proactive in coordinating the neutrino program including beam requirements and provide overall scientific stewardship.
  - It is recommended that long range planning contingent on the results from the present round of neutrino experiments should be undertaken.

➜ Focus Group formed by Directorate to formulate a strategic plan for short-baseline experiments at Fermilab

- Timeline:-
  - Short-Baseline Neutrino Workshop, FNAL, May 12-14, 2011
  - Fundamental Physics at the Intensity Frontier, 30 Nov – 2 Dec, 2011, Rockville, MD ➔ neutrino group report
  - Sterile Neutrinos at the Crossroads, 25-28 September 2011, Blacksburg, VA ➔ white paper on sterile neutrinos
  - Short Baseline Focus Group Community Meeting: 21 March 2012
  - Focus Group's final report released 7 June 2012

Short Baseline Focus Group Summary

A new short-baseline accelerator-based experiment is well motivated and is necessary to definitively resolve ($\geq 5\sigma$) the LSND/MiniBooNE tensions with three-flavor mixing.

Recommendations

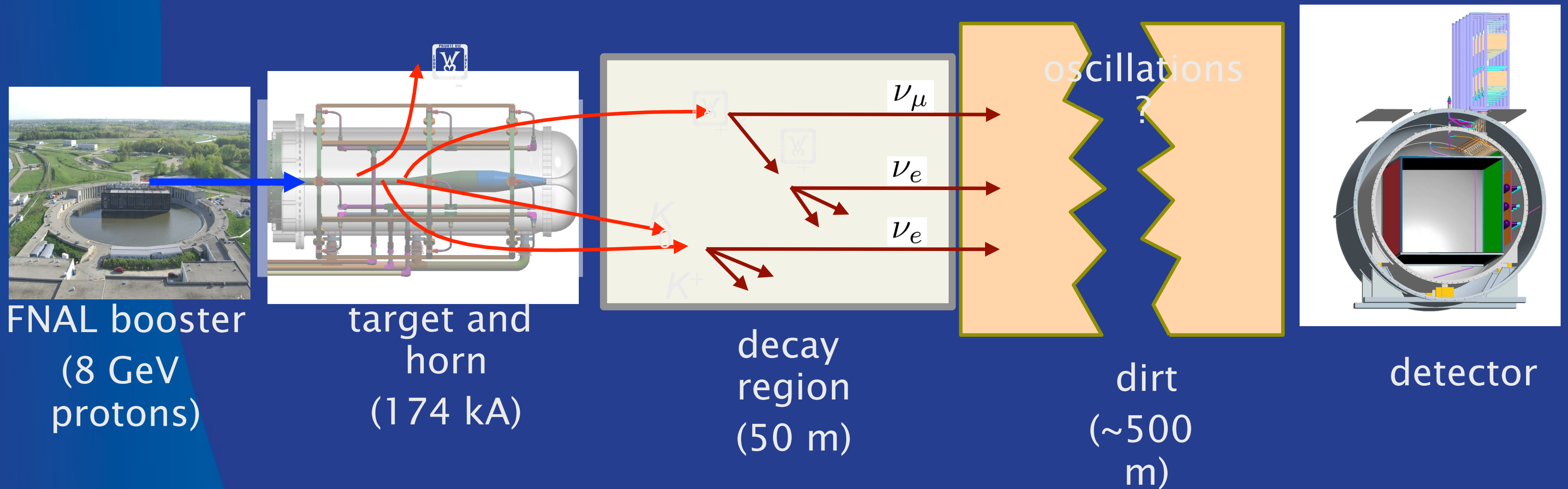
1. There be a new SBL experiment at FNAL.
2. The new experiment be pursued as vigorously as is practical.
3. There be a call for proposals → evaluated by the PAC at one time.
4. If sterile ν discovered, the SBL at FNAL program be further expanded.
5. Cross-section/particle production measurement-needs must be quantified for each proposal.
6. Study needed of potential for increasing the beam power at 8 GeV.

Final Report: http://sbl-neutrinos.fnal.gov/

The MicroBooNE Experiment

MicroBooNE: Liquid Argon Time Projection Chamber

70 ton fiducial volume LArTPC to be exposed to the Booster and NuMI Neutrino Beams

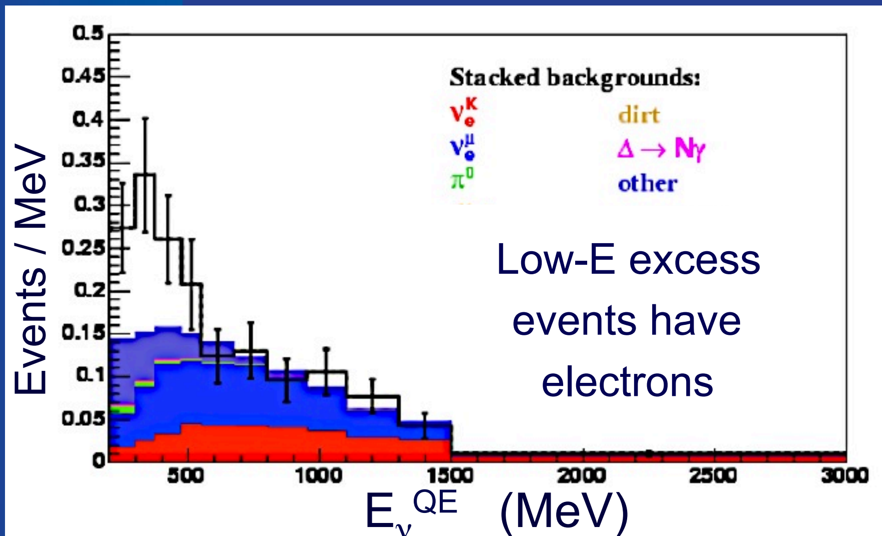


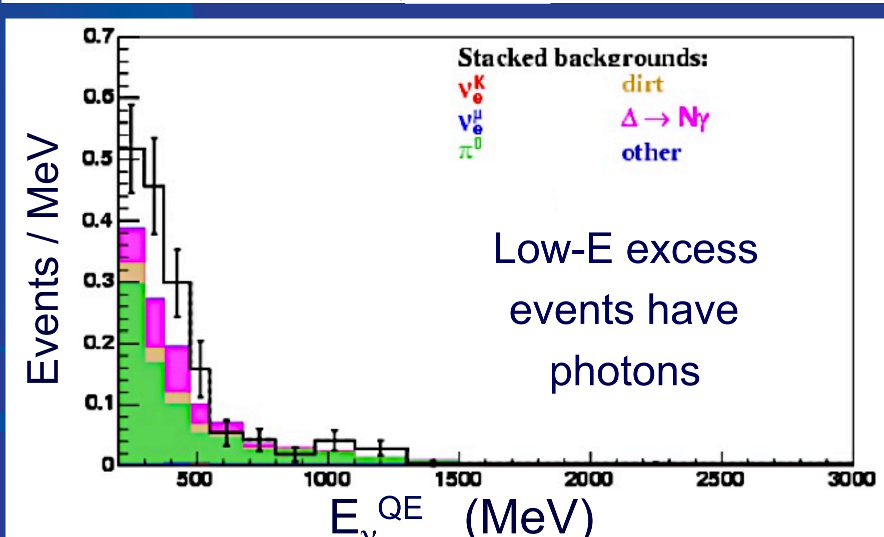
Look for low energy neutrino phenomena

- MiniBooNE low energy excess – distinguish electrons from gammas
- Low energy neutrino cross sections
- R&D for LArTPCs

95 collaborators from 16 institutions in 3 countries

MicroBooNE Check of MiniBooNE Low Energy Excess





6 x 10^{20} pot in neutrino mode (2-3 year run, starting 2014)

If the MiniBooNE low energy excess is due to electrons, MicroBooNE expects a 5σ signal

If the MiniBooNE low energy excess is due to photons, MicroBooNE expects a 4σ excess

Future Short Baseline Possibilities

Currently 3 short baseline experiments are in the process of moving from LOI to Proposal

- LAr1
  - Two LAr detectors in the Booster & NuMI beams
- νStorm
  - Neutrinos from a muon storage ring aimed at near and far magnetized iron detectors
- MiniBooNE with Scintillator added
  - Probe low energy excess by telling apart proton and neutron emission

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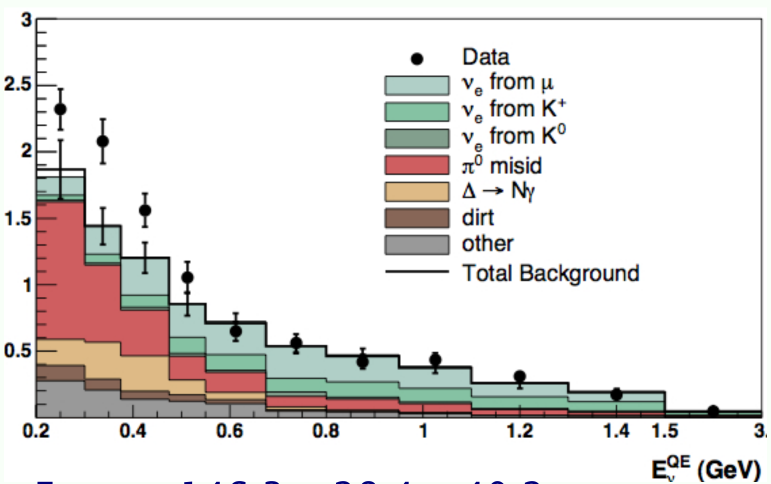
MiniBooNE ν_e and anti-ν_e Appearance Two Years Ago

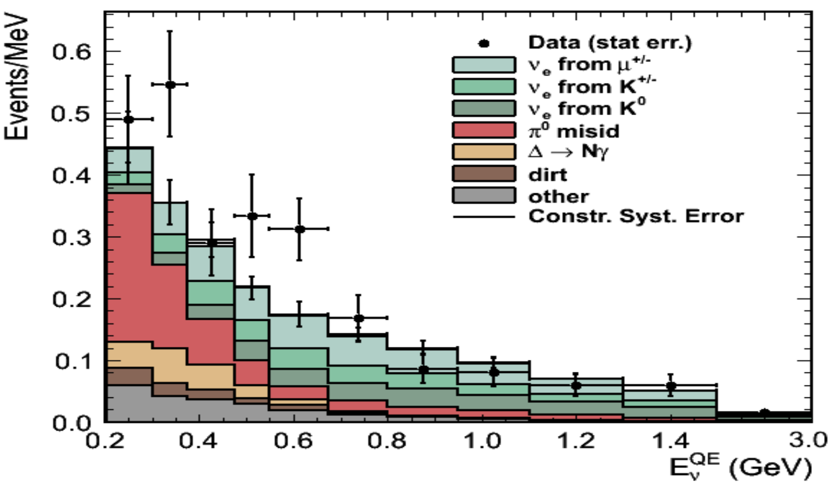
The low energy excess seen in neutrino mode was not seen as strongly in anti-neutrino mode

6.7e20 POT neutrino mode



Excess: 146.3 ± 28.4 ± 40.2

5.7e20 POT anti-neutrino mode

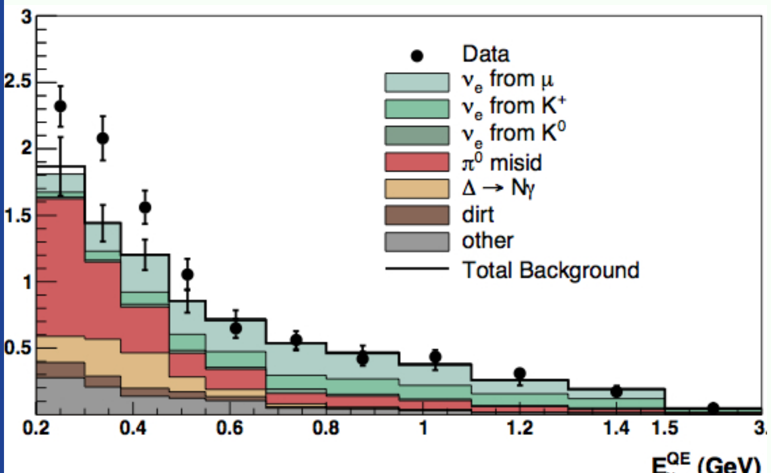


Excess: 43.2 +/- 15.3 +/- 16.5

MiniBooNE ν_e and anti-ν_e Appearance Now

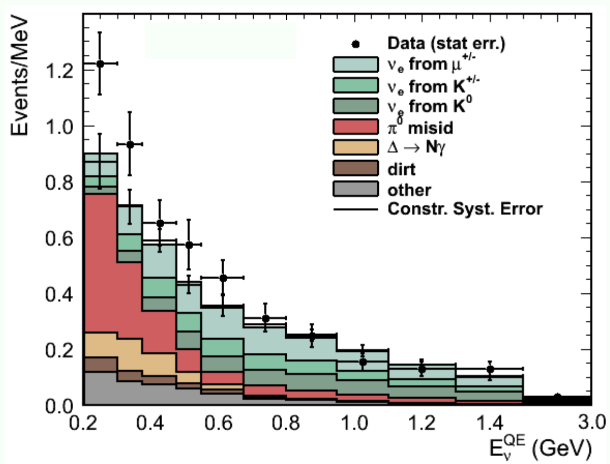
- Doubling of the anti-neutrino dataset in the last 2 years has enabled the resolution of MiniBooNE neutrino-antineutrino differences in ν_e appearance.

6.7e20 POT neutrino mode



Excess: 146.3 ± 28.4 ± 40.2

11.3e20 POT anti-neutrino mode



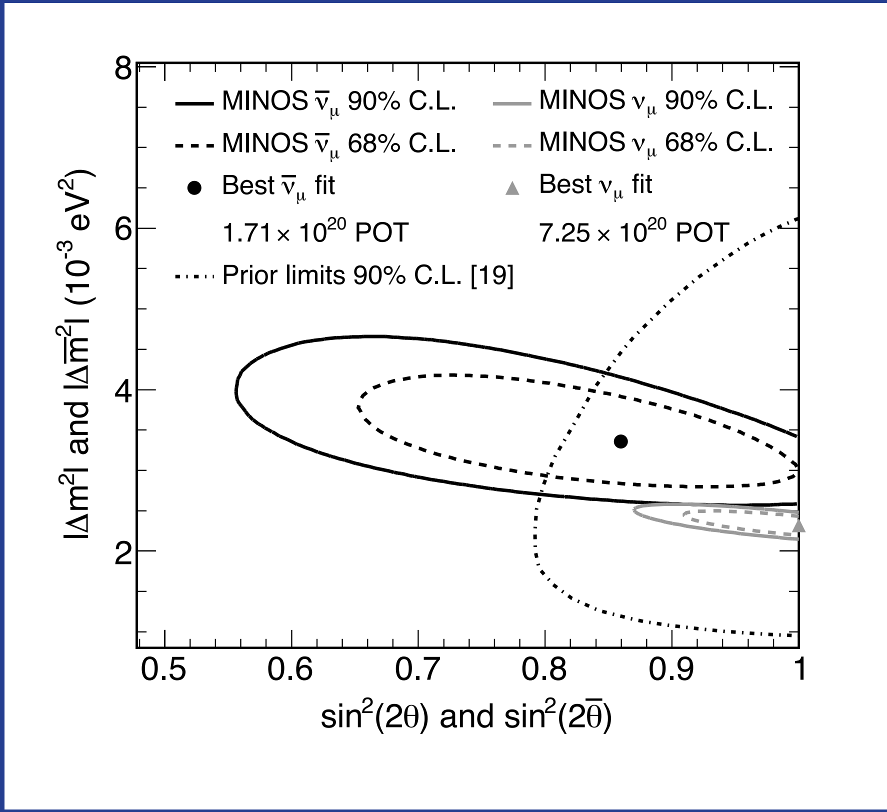
Excess: 77.8 +/- 20.0 +/- 23.4

- Low energy excess appears in both modes.

- It is not clear what MiniBooNE is telling us, but at least the picture is consistent between neutrino and anti-neutrino modes

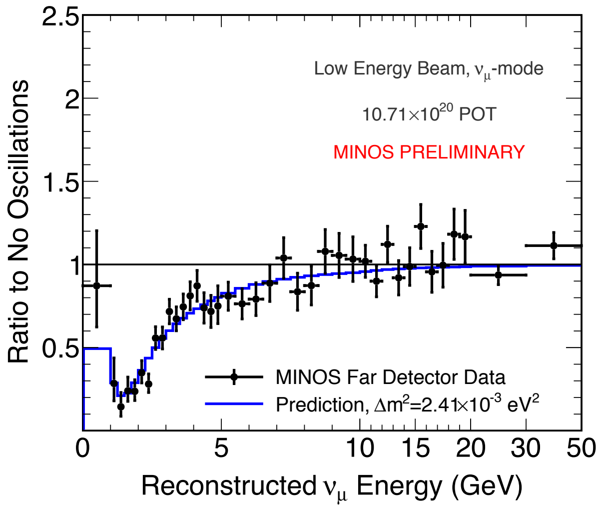
MINOS ν_μ and anti-ν_μ Disappearance Two Years Ago

Oscillation parameters from ν_μ disappearance barely consistent with those from anti-ν_μ disappearance

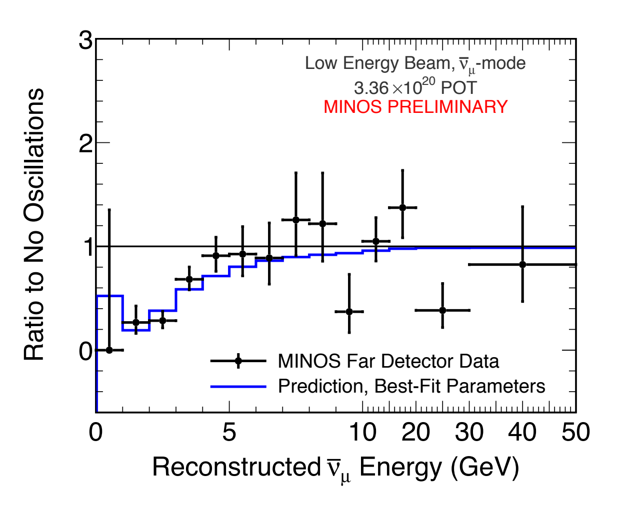


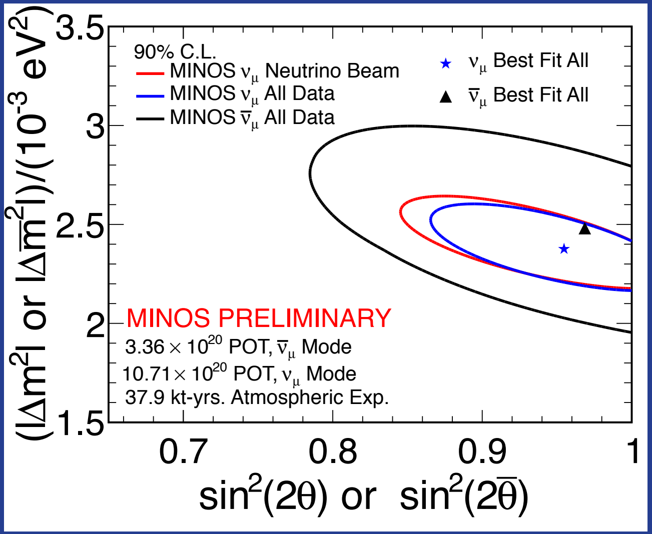
Fermilab

MINOS ν_μ and anti-ν_μ Disappearance Now



Fermilab program planning decision to grant extra anti-neutrino running for MINOS





New data has resolved tension between neutrino and antineutrino results

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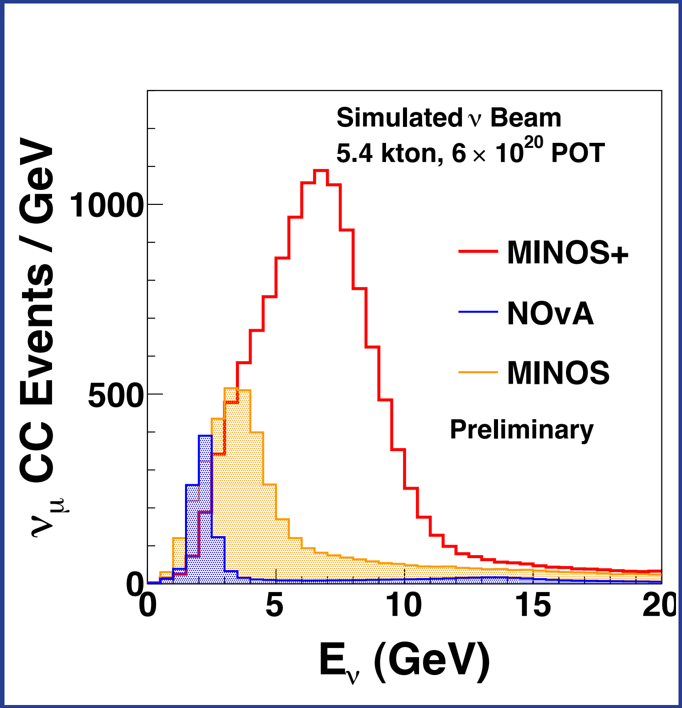
MINOS+

Continued running of the MINOS far detector in the NOvA beam (MINOS near detector will be running anyway for MINERvA)

Running at the higher energies for which the MINOS detector was actually optimized

(Remember that when MINOS was designed the best fit Δm_{32}^2 was higher and so the energies relevant to the FNAL-Soudan baseline were higher)



MINOS+ Capabilities

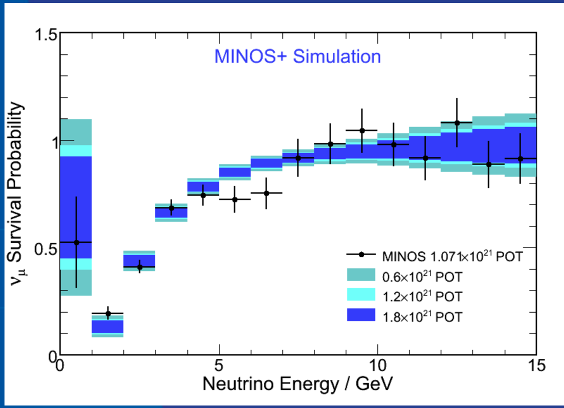
1. Improved measurement of θ_{23} and Δm_{32}^2
2. Study of high energy neutrinos
3. Search for sterile neutrinos
4. Search for tau neutrinos
5. Atmospheric neutrinos
6. Non-standard interactions
7. Measurement of the neutrino time of flight
8. Search for extra dimensions

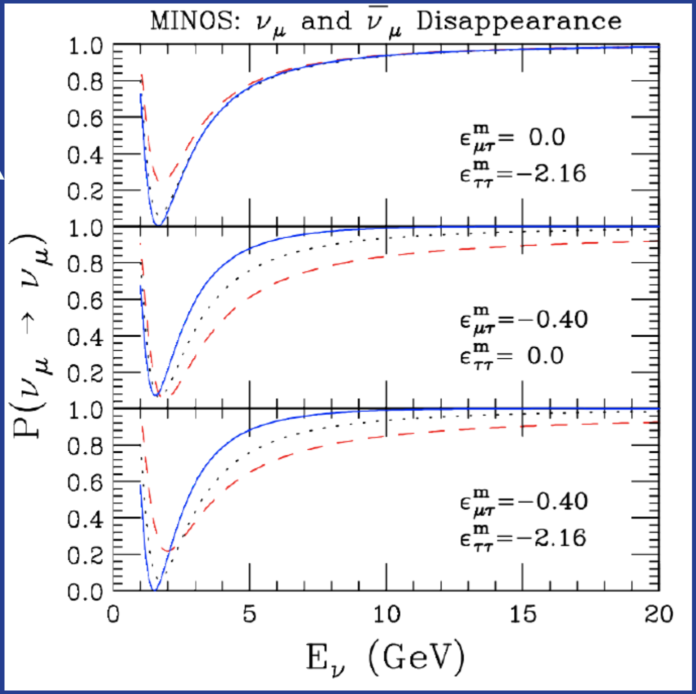
MINOS+ Non-Standard Interactions

If neutrinos have non-standard interactions these will produce additional matter effects beyond those expected when the beam traverses long distances and modify the oscillation probability

e.g. J.Kopp, P.A.N.Machado, and S.Parke Phys. Rev. D82:113002 (2010)

Note the high energy differences between ν_μ and anti-ν_μ disappearance





Fermilab

MINOS+ Neutrino Time of Flight Measurement

Over the last year the timing hardware of MINOS has been extensively upgraded to have better than 1ns precision

Last week MINOS announced a new result taken with only ~a month of data

$$(v-c)/c = 1.0 \pm 1.1 \times 10^{-6}$$

(uncertainty dominated by knowledge of baseline)

MINOS+ will be capable of measuring to the level:-

$$(v-c)/c < 5 \times 10^{-7}$$

Not a relevant limit on neutrino mass (corresponds to about 2 MeV/c^2)
but a measurement with a demonstrated level of interest!

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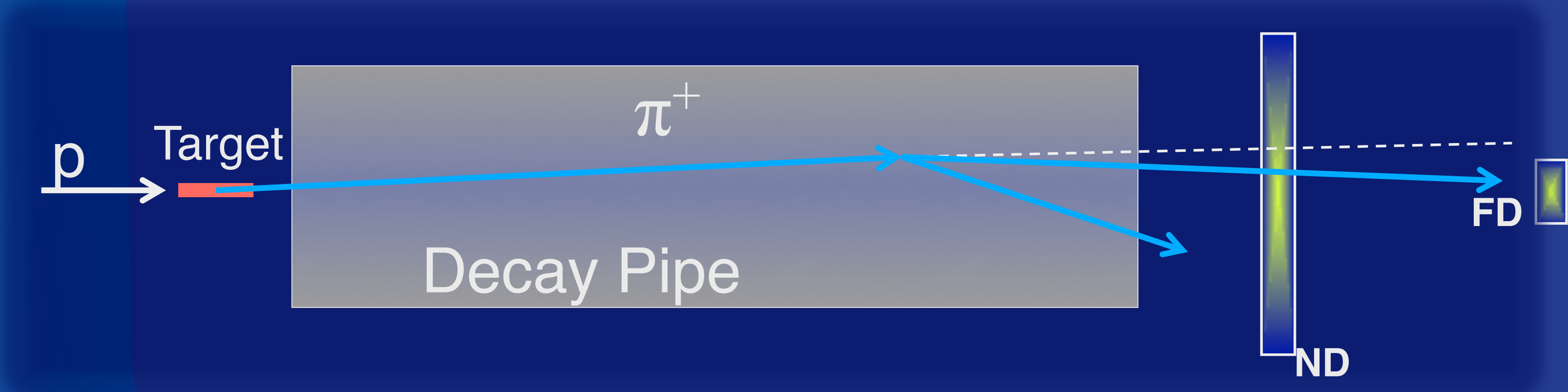
The Need for Neutrino Cross-Section Measurements

Far spectrum without oscillations is similar, but not identical to the Near spectrum!



Adapted from P. Vahle

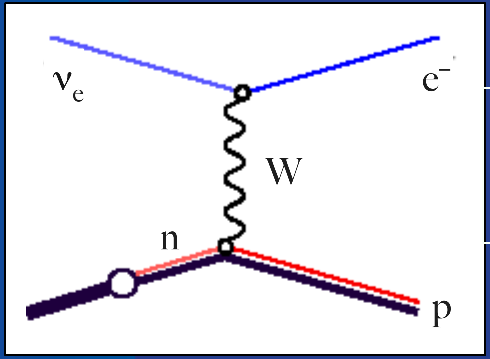
- Near detector predicts Far detector un-oscillated rate up to corrections
- Neutrino energy depends on angle wrt original pion direction and parent energy
  - Angular distributions different between Near and Far
  - Higher energy pions decay further along decay pipe
  - Neutrino source is pointlike as seen from far detector but not from near detector

$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Therefore you still need flux prediction and cross-section knowledge for a precision measurement even if you have a Near detector

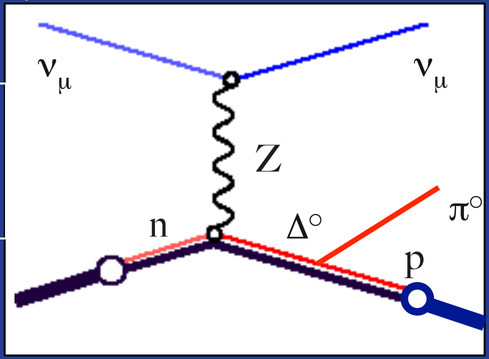
Some Relevant Cross-Section Examples

ν_e Charged Current Quasi-Elastic (CCQE)



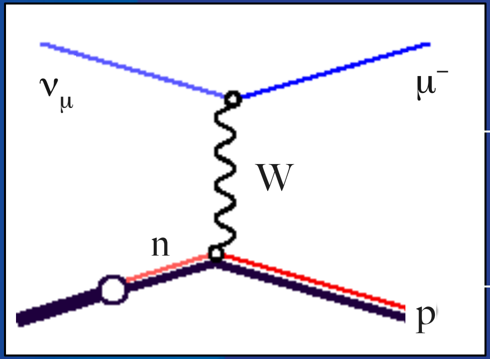
Used as ν_e appearance signal channel

ν_μ Neutral Current π^0 (NCπ^0)



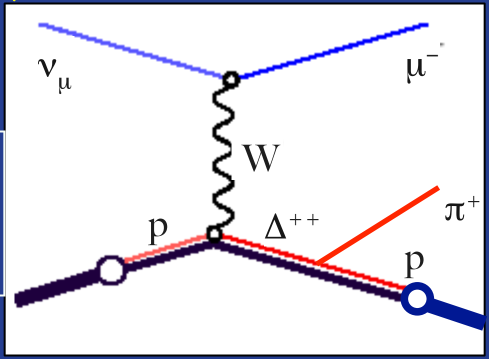
Background to ν_e appearance (π^0 fakes an e^-)

ν_μ Charged Current Quasi-Elastic (CCQE)



Used as ν_μ disappearance signal channel

ν_μ Charged Current π^+ (CCπ^+)



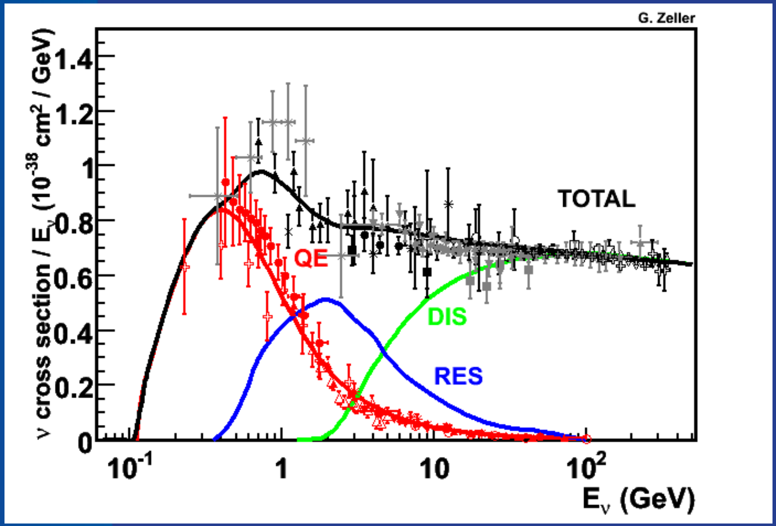
Background to ν_μ disappearance (π^+ gets lost)

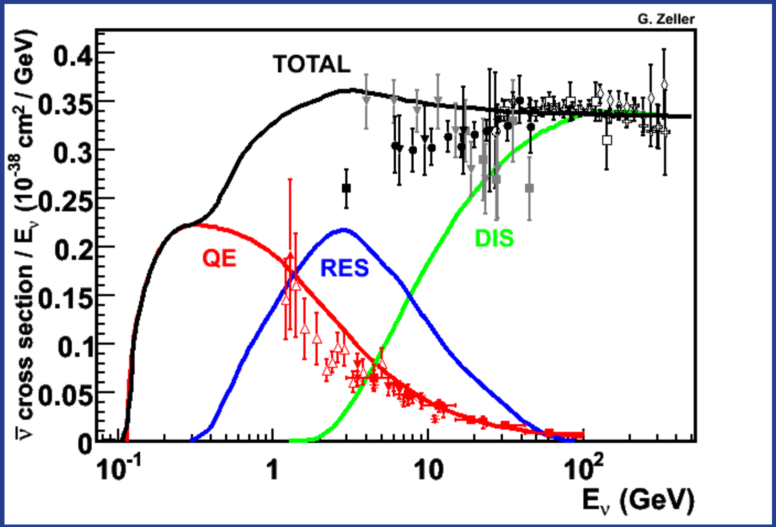
And a number of less common processes (e.g. radiative Δ^0 decay)

And all the anti-neutrino version of these processes

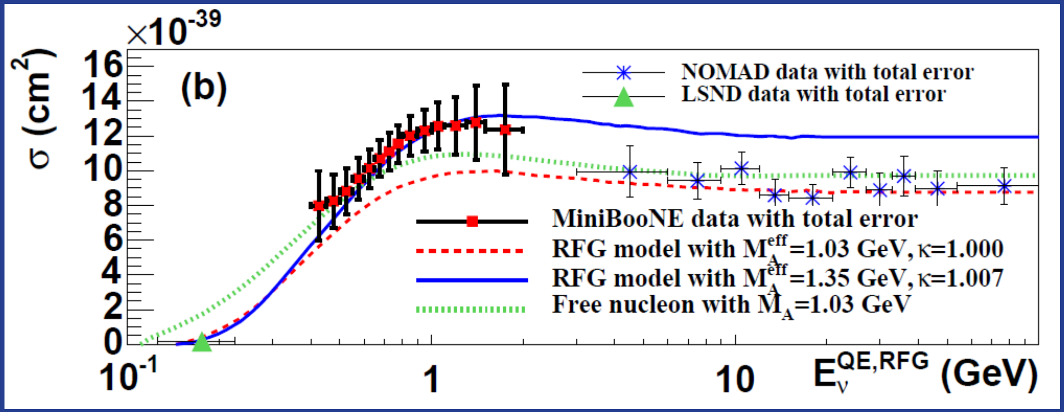
Status of GeV Neutrino Cross-Sections

Neutrino cross-sections around 1 GeV are not very well measured





J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys., 2012.



Energy dependence and scale of measured QE cross-section not sufficiently well understood

Fermilab

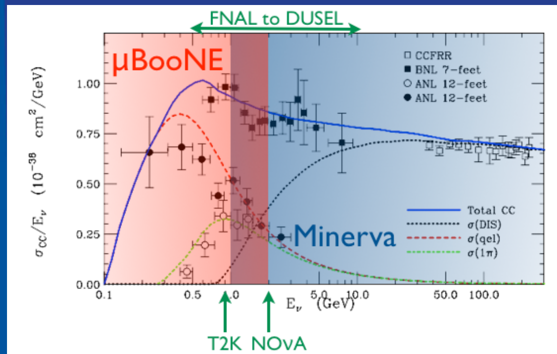
Fermilab Neutrino Cross-Section Measurements

Experiment	Beamline	Status	Nuclear Target	capability
ArgoNeut	NuMI	Completed 2010	Ar	LAr TPC but tiny dataset
MINOS	NuMI	Completed 2012	Fe	No detailed final state ID
MINERvA	NuMI	Running	He, C, O, Fe, Pb	Fine grained tracking calorimeter
NOvA	NuMI	Under Construction	C	Fine grained tracking calorimeter
MINOS+	NuMI	Fermilab Approved	Fe	No detailed final state ID
MiniBooNE	BNB	Completed 2012	C	Some final state ID
SciBooNE	BNB	Completed 2008	C	Small, fine grained tracking calorimeter
MicroBooNE	BNB	Under Construction	Ar	LAr TPC

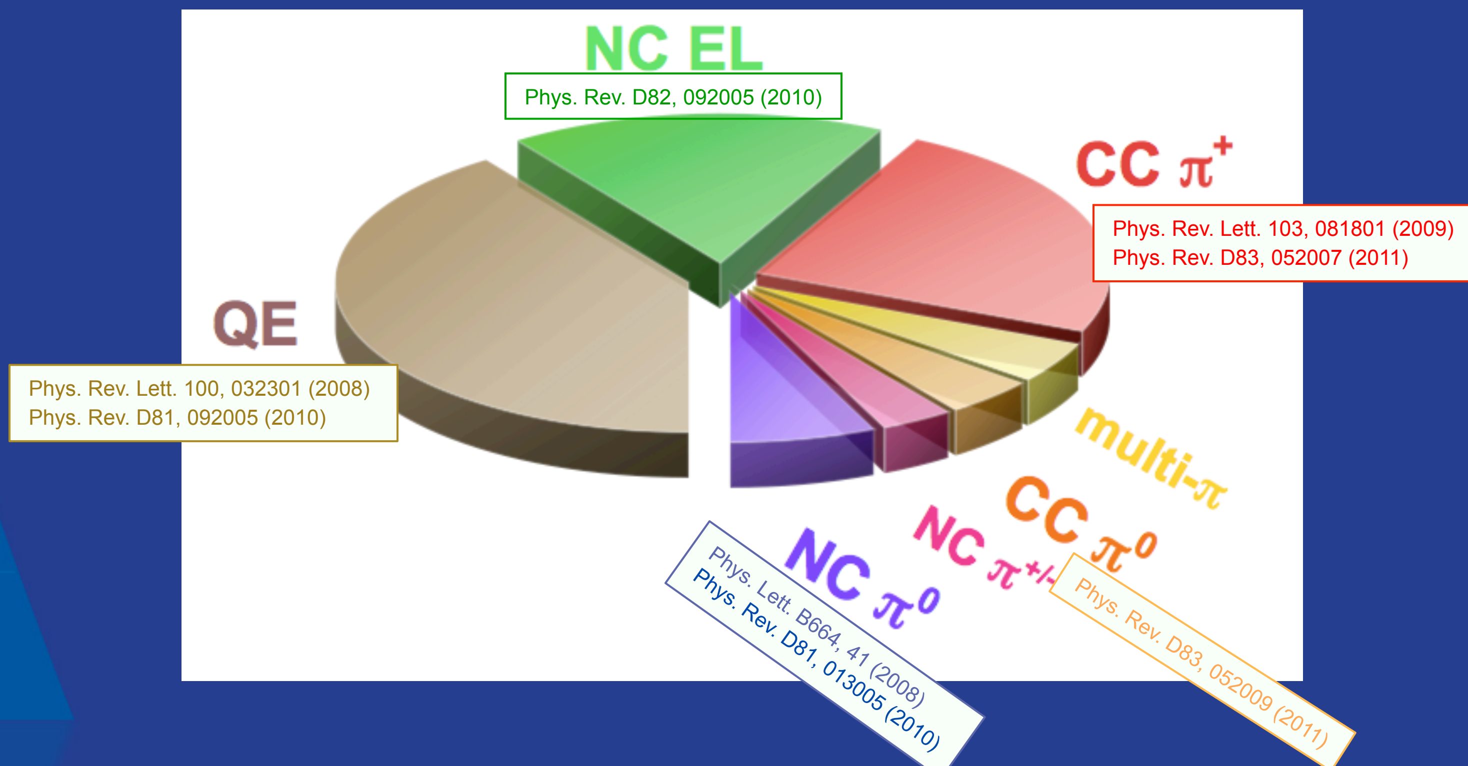
Current and future oscillation experiments need

- Detailed final state information
- On Carbon, Oxygen, and Argon
- For electron neutrinos and muon neutrinos
- For neutrinos and anti-neutrinos

MiniBooNE Cross-Section Results

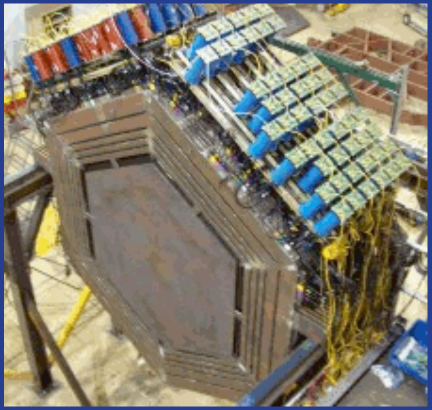


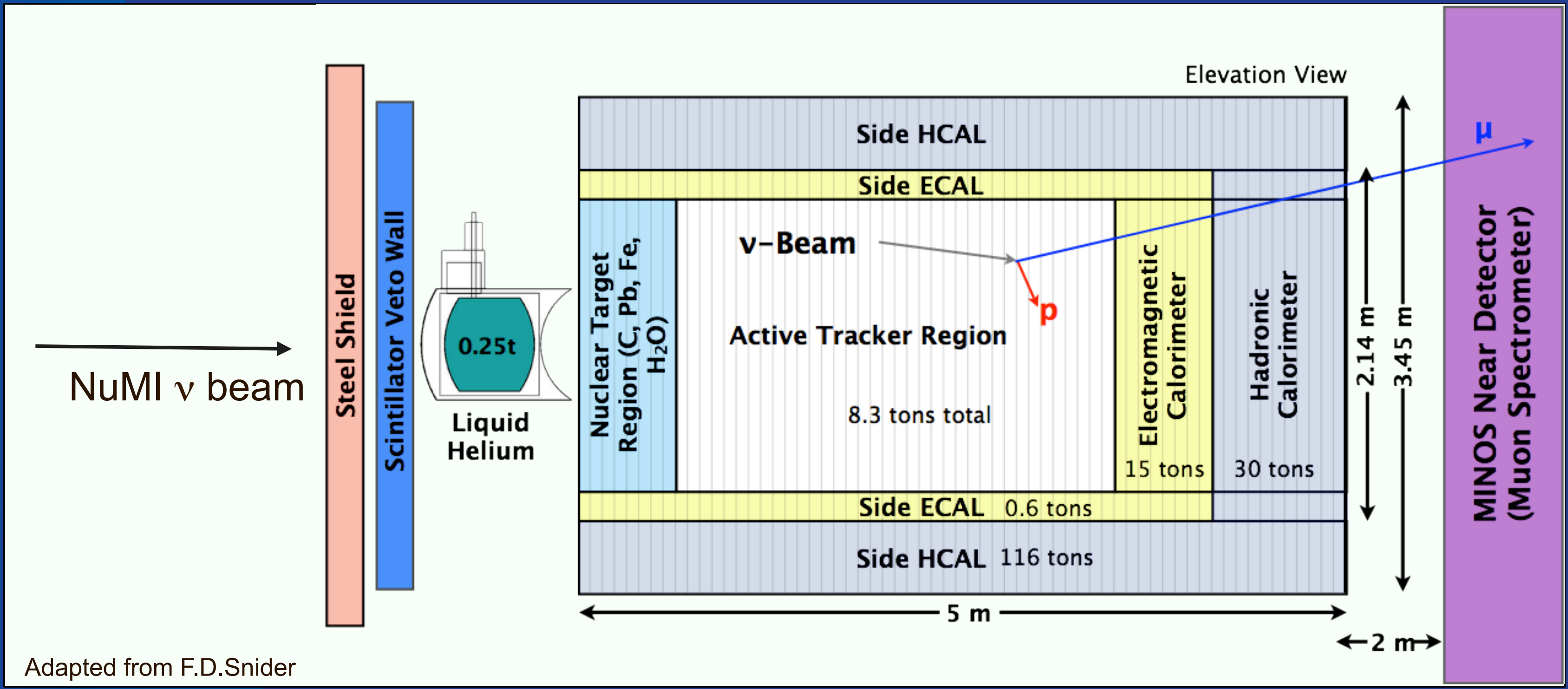
MiniBooNE measures cross-sections in exactly the 1 GeV range of interest to T2K, NOvA, and LBNE



MINERvA

- 120 stacked modules, mostly planes of scintillator strips
- Fully active, finely-segmented tracking region in center
- LHe and nuclear target region on upstream side
- Side and end EM and hadronic calorimeter regions
- MINOS near detector used as muon spectrometer

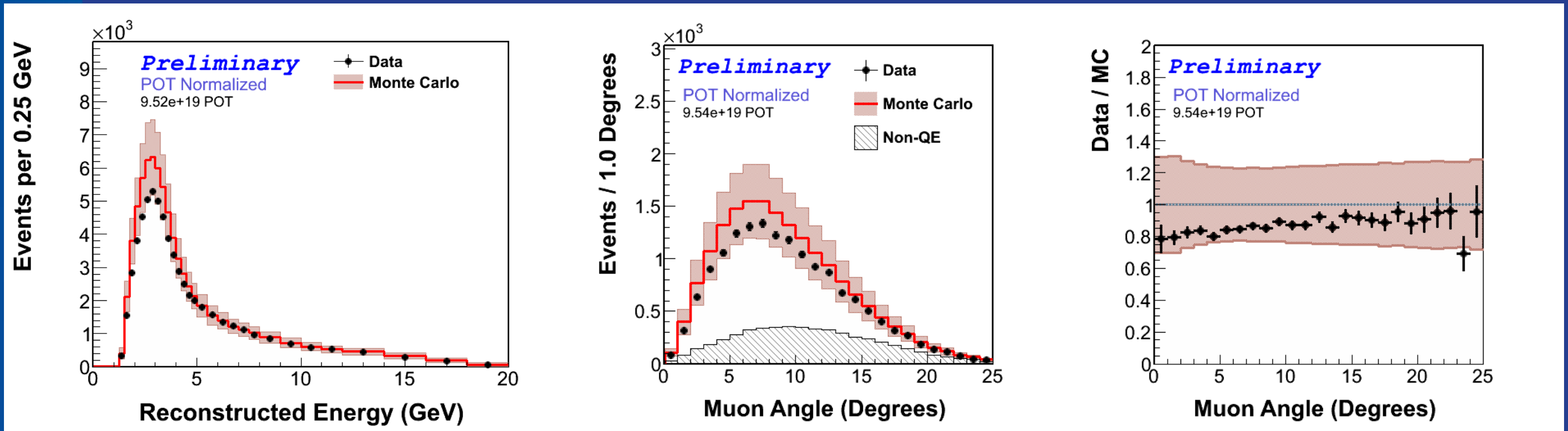




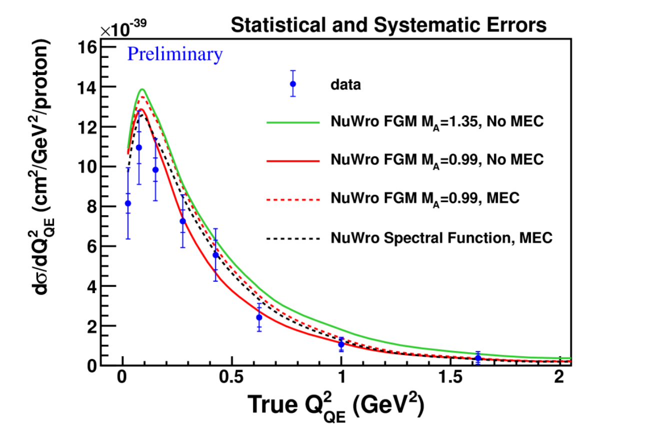
70 collaborators from 21 institutions in 8 countries

MINERvA Latest Results

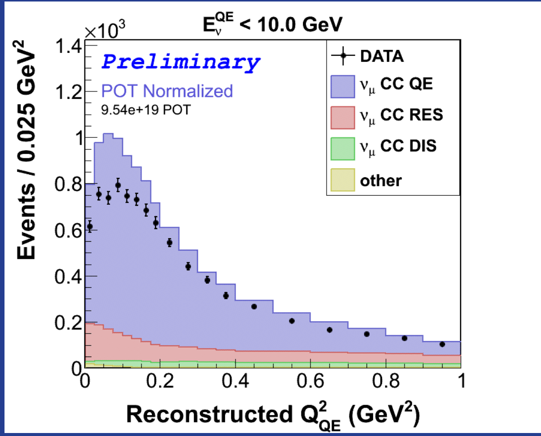
Neutrino CC Inclusive kinematic distributions



Anti-neutrino CCQE Cross-section



Neutrino CCQE Q^2 distribution

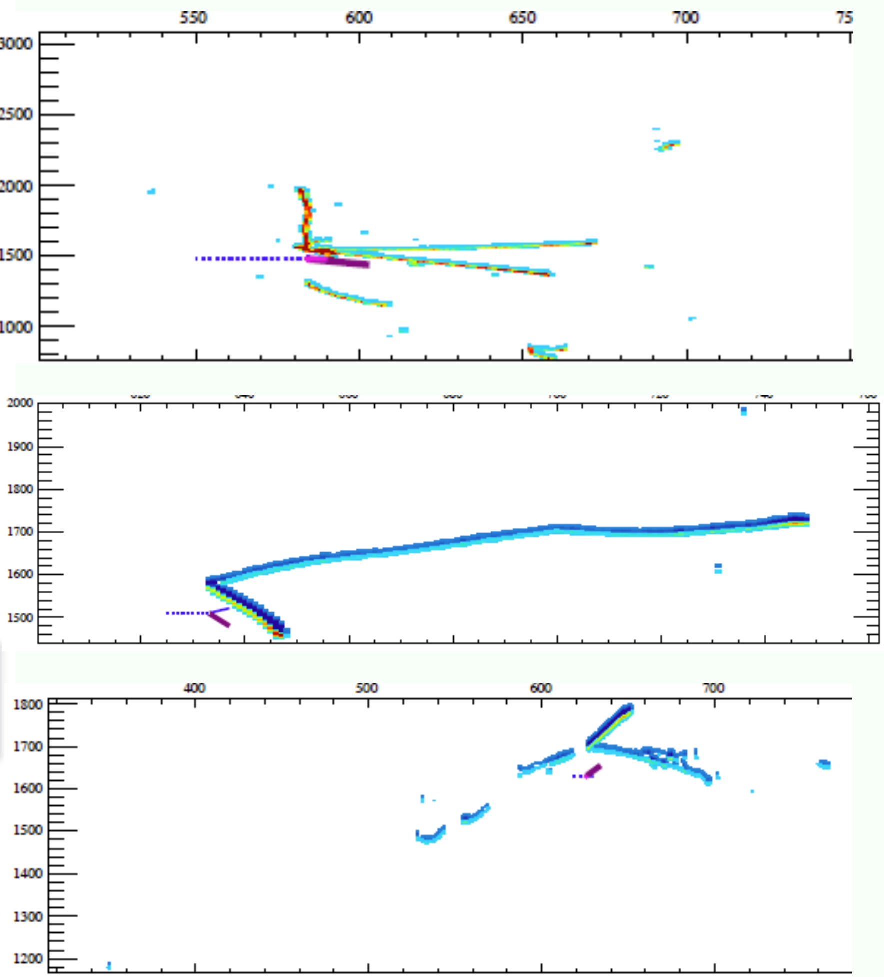


Fermilab

Future MicroBooNE Cross-Section Measurements

Expected event rates for 6.6×10^{20} POT

production mode	# events
CC QE ($\nu_\mu\, n \to \mu^-\, p$)	60,161
NC elastic ($\nu_\mu\, N \to \nu_\mu\, N$)	19,409
CC resonant π^+ ($\nu_\mu\, N \to \mu^-\, N\, \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu\, n \to \mu^-\, p\, \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu\, N \to \nu_\mu\, N\, \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu\, N \to \nu_\mu\, N'\, \pi^\pm$)	4,796
CC DIS ($\nu_\mu\, N \to \mu^-\, X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu\, N \to \nu_\mu\, X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu\, A \to \nu_\mu\, A\, \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu\, A \to \mu^-\, A\, \pi^+$)	2,626
NC kaon ($\nu_\mu\, N \to \nu_\mu\, K\, X$)	39
CC kaon ($\nu_\mu\, N \to \mu^-\, K\, X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657



And Neutrino Measurements not directly coupled to the Big Neutrino Questions

- MINERvA measurements of
  - structure functions
  - the A dependence of inclusive neutrino cross-sections
  - physics more coupled to the SeaQuest/QCD part of the lab's program
- Feasibility studies of a neutrino coherent scattering measurement
  - Using neutrinos from the Booster Neutrino Beamline
  - Stopped pion and muon decay
  - Currently investigating the neutron background
  - Project of JongHee Yoo (Wilson Fellow)

Summary

- Fermilab’s current neutrino program is world leading and has contributed significantly to our understanding of neutrino physics

- Fermilab’s planned future neutrino program will see it play an even larger role in the global effort

- The last decade has been revolutionary for neutrino physics and the next decade promises more. Fermilab will be the heart of the global program

Fermilab Experimental Thrusts in Neutrino Physics

1) Reveal the pattern of neutrino masses and mixings
   - What are the neutrino masses? **No plans to address at Fermilab**
   - Are neutrinos their own anti-particles? **No plans to address at Fermilab**
   - Is θ_{23} maximal? **MINOS ➔ NOvA ➔ LBNE**
   - How are the masses ordered? **NOvA ➔ LBNE**
   - Is CP violated? **LBNE**

2) Discover if the situation is more complex than 3 neutrinos with Standard Model interactions
   - Can we independently check the θ_{13} measured by reactor experiments? **MINOS ➔ NOvA ➔ LBNE**
   - Are the LSND and MiniBooNE anomalies new physics? **MiniBooNE ➔ MicroBooNE**
   - Are neutrinos and anti-neutrinos oscillating differently in current experiments? **MiniBooNE, MINOS ➔ NOvA**
   - Do neutrinos interact with matter in any non-standard ways? **MINOS+**

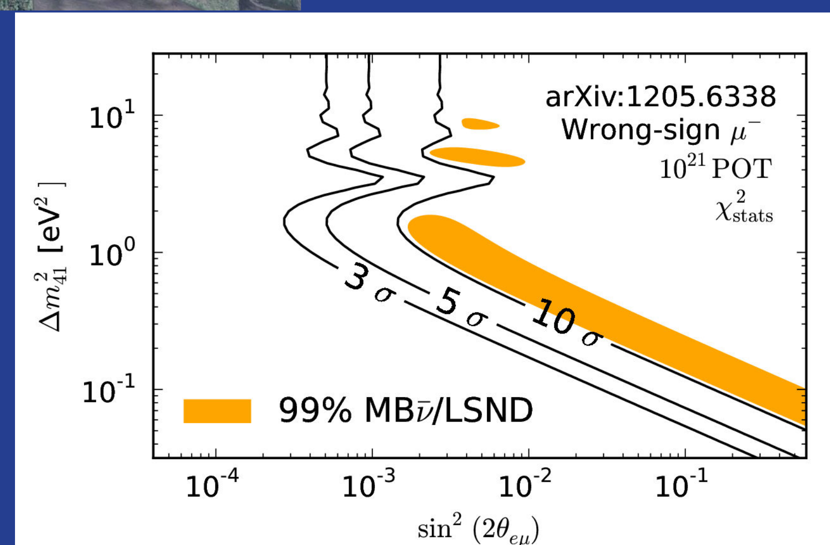
3) Carry out the neutrino engineering measurements that make 1) and 2) possible
   - **MiniBooNE, SciBooNE, MINERvA, ArgoNeut, MicroBooNE**

νStorm

Magnetized iron detector (a la MINOS) in D0 Building

Few GeV muon storage ring with ~150m straight sections

Near hall with magnetized iron near detector + separate cross-section detector



$\nu_e \rightarrow \nu_\mu$ appearance

CPT invariant channel to MiniBooNE